

BSM Benchmarks for Muon Colliders: IV

Muon Collider Physics Benchmarks Workshop

PITT PACC - University of Pittsburgh

Nov 17, 2023

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Fermilab



*Federico
Meloni, DESY*



*Rosa Simoniello,
CERN*



*Jose Zurita,
U. Valencia*

RC, Federico Meloni, Jose Zurita, ArXiv: 2312.xxxxx

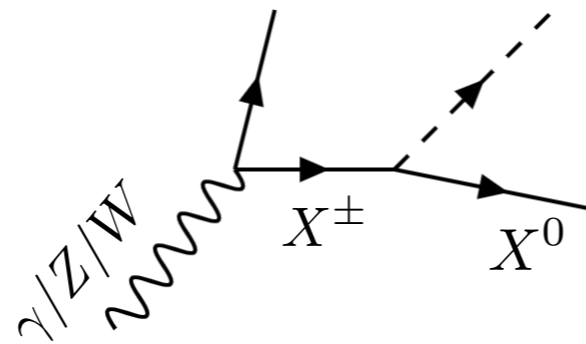
*RC, Federico Meloni, Rosa Simoniello, Jose Zurita, JHEP **06** (2021) 133*

Question:

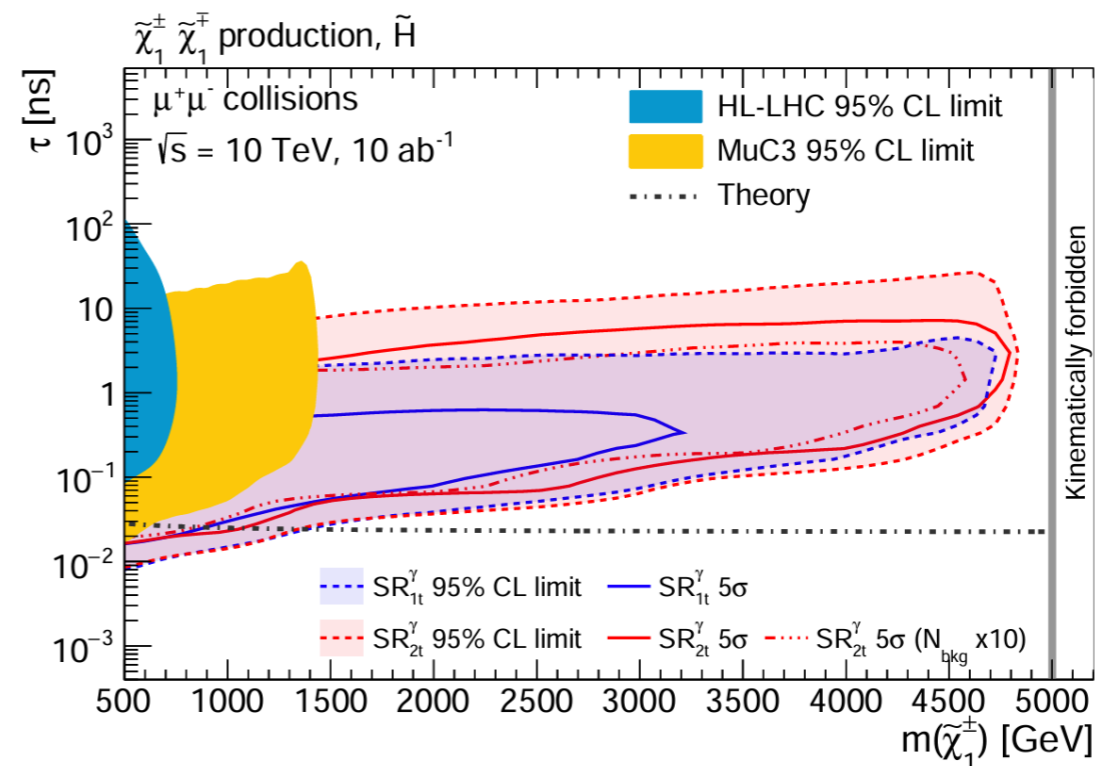
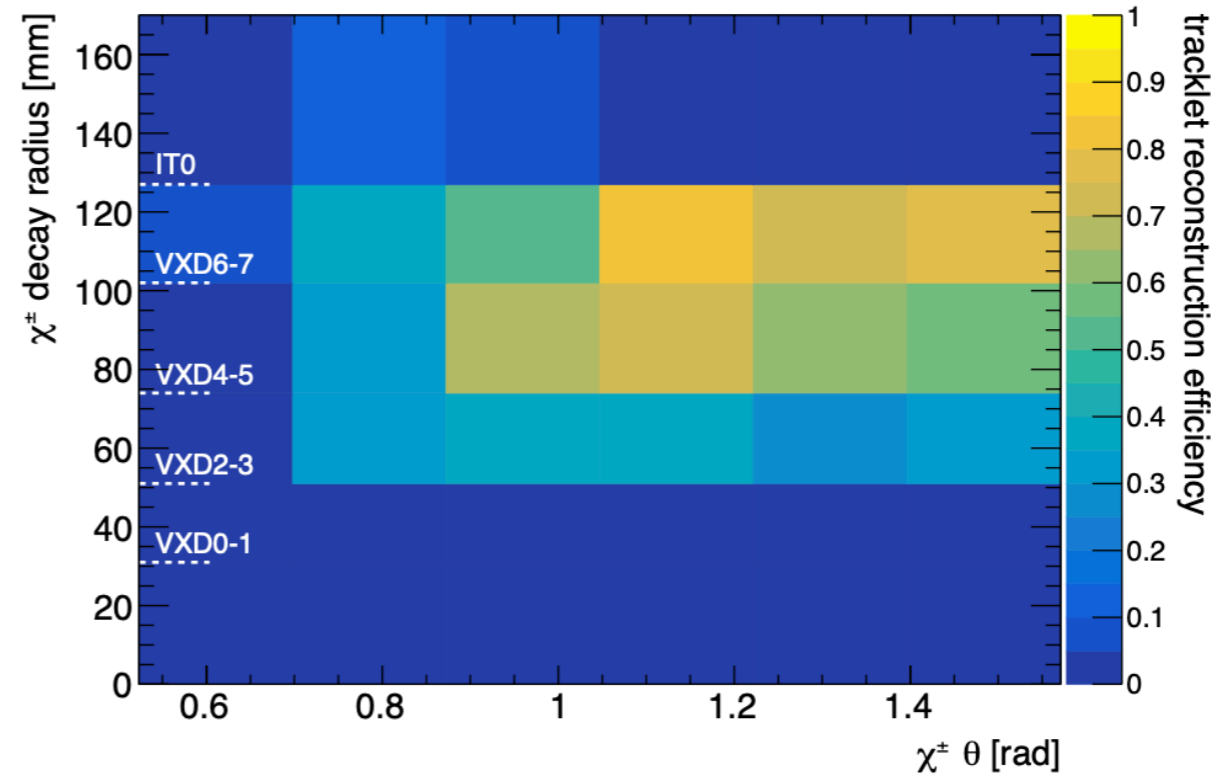
Can we identify BSM motivated scenarios with exotic signals that can have implications in detector and accelerator/facility design?

Motivation	Theoretical scenario	Candidate particle(s)	Exotic Signals (Potential Implications for Detector/Facility Design)								
			Boosted objects	Small splittings	Stopping particles	Disappearing tracks	Displaced vertices	Exotic tracks	Emerging jets	Exotics in the mu system	Forward detector
Exotics	SM+singlet	S, a	x								x
	2HDM	H^\pm, H^0, A	x	x		x	x		x	x	
	New gauge groups	Z', W', γ'	x								x
	VLF	Q', L'	x	x		x					
	HNL	N_i				x	x			x	x
	Leptoquarks	\tilde{R}_2, U_1 (UV motivated)	x	x							
	Quirks	$q' \bar{q}'$			x				x	x	
	Hidden valleys	(bound states) $g' g'$					x		x	x	x
Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	x	x	x						
		$\chi^\pm, \chi^0, \tilde{\tau}$ (not colored)	x	x		x			x		x
	Composite	$X_{5/3}, T_{2/3}$	x	x							
	Extra dimensions	G_{KK}	x								
	Neutral naturalness	Glueballs, sQuirks			x		x		x	x	x
DM	Z portal	EWinos-like (inelastic)				x	x		x		
	H portal	S (Z2 symmetric)									
	Nu portal	ν_s									x
	U(1) portal	$U(1)_{B-L_i-L_j}$					x			x	x

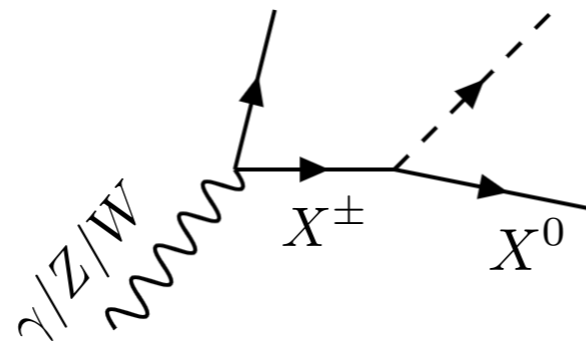
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Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	
		$\chi^\pm, \chi^0, \tilde{\tau}$ (not colored)	x
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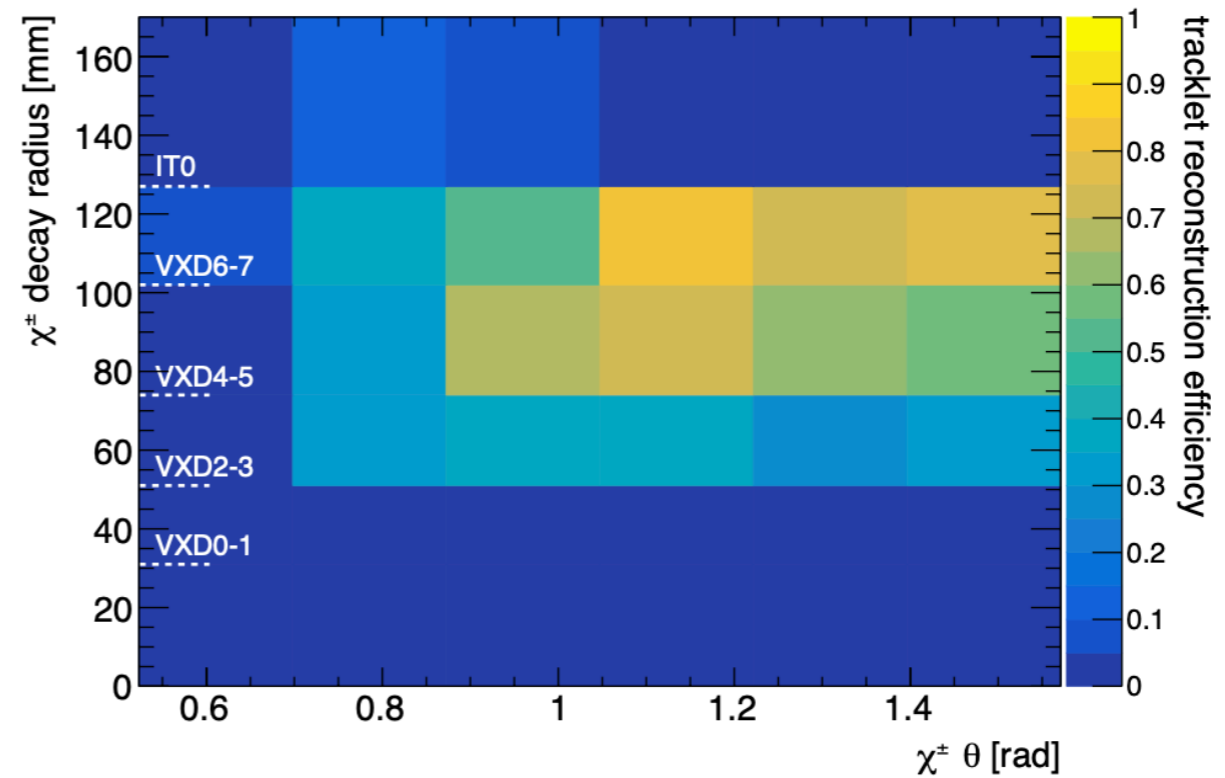
RC, F. Meloni, R. Simoniello, J. Zurita,
JHEP 06 (2021) 133



Motivation	Theoretical scenario	Candidate particle(s)	Exotic Signals
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RC, F. Meloni, R. Simoniello, J. Zurita,
JHEP 06 (2021) 133



Can be useful for:

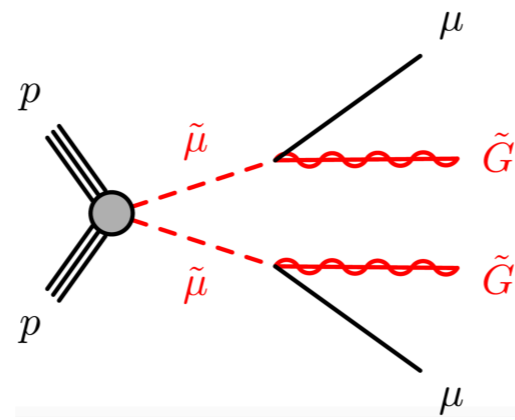
DT Beyond Minimal WIMPs:

- Coannihilation Scenarios (small mass gaps)
- Freeze-In scenarios with low T reheat (small couplings)

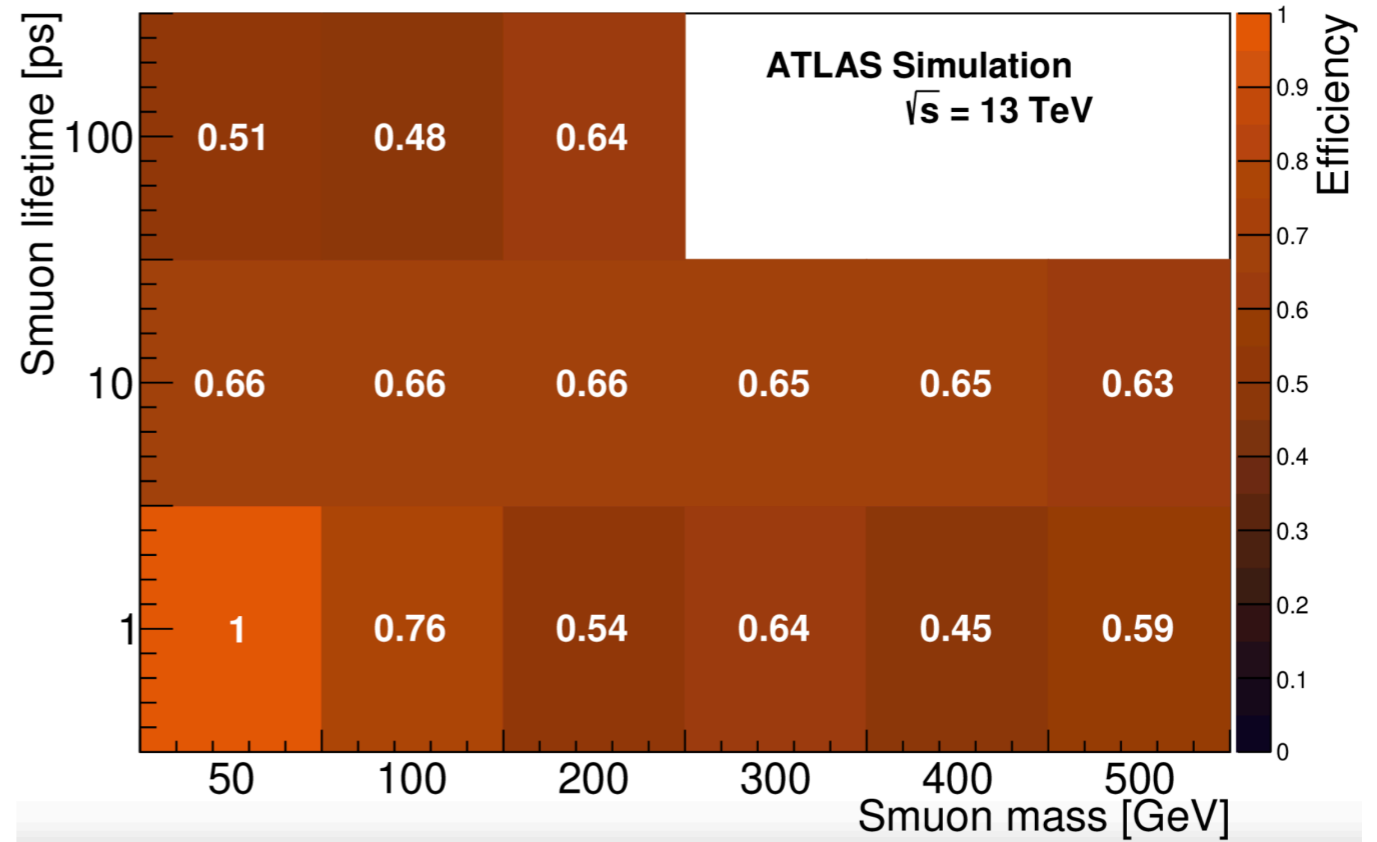
B-mesons:

- Potential backgrounds for DT searches
- Flavor physics

Motivation	Theoretical scenario	Candidate particle(s)	Exotic Signals	
			Exotic tracks	
Exotics	SM+singlet	S, a		
	2HDM	H^\pm, H^0, A		
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ATLAS Collaboration, Phys. Lett. B 846 (2023) 138172

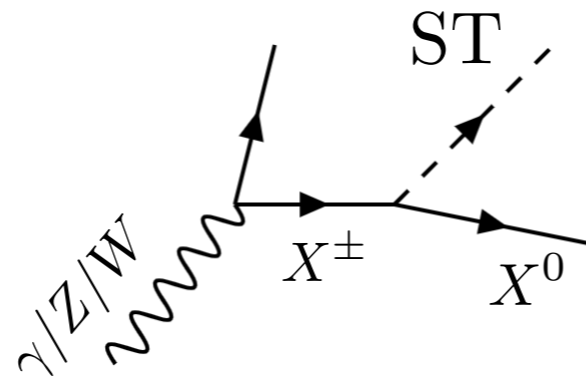


At the MuC?

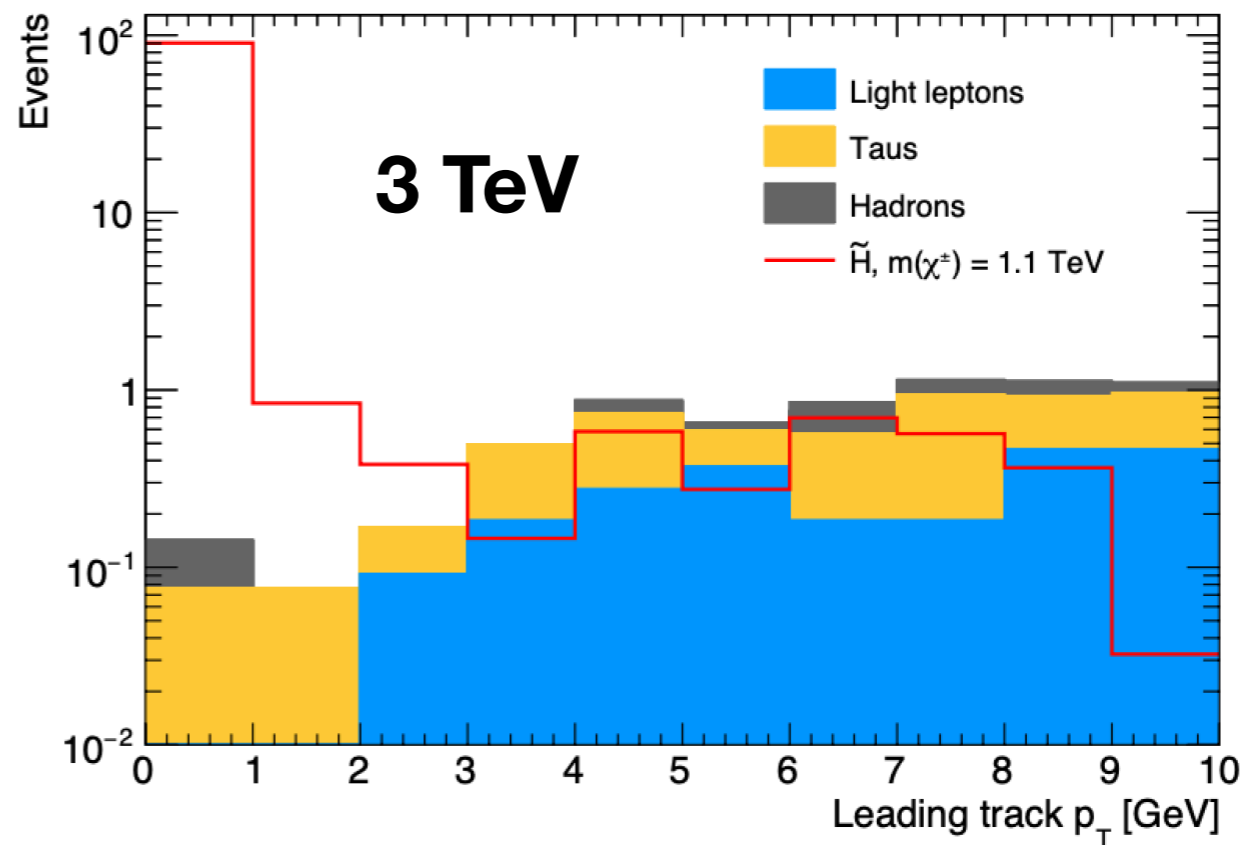
Can be useful for:

Sleptons, Heavy Neutral Leptons, Neutralinos

Motivation	Theoretical scenario	Candidate particle(s)	Exotic Signals	
			Exotic tracks	
Exotics	SM+singlet	S, a		
	2HDM	H^\pm, H^0, A		
	New gauge groups	Z', W', γ'		
	VLF	Q', L'		
	HNL	N_i		
	Leptoquarks	\tilde{R}_2, U_1 (UV motivated)		
	Quirks	$q' \bar{q}'$ (bound states)	x	
	Hidden valleys	$g' g'$	x	
	Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	
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Composite		$X_{5/3}, T_{2/3}$		
DM	Extra dimensions	G_{KK}		
	Neutral naturalness	Glueballs, sQuirks	x	
	Z portal	EWinos-like (inelastic)	x	
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	Nu portal	ν_s		
	U(1) portal	$U(1)_{B-L_i-L_j}$		



Good News!!!



Scientists report that the 3 TeV MuC has the potential to discover the thermal Higgsino-like Minimal WIMP!

The key is to reconstruct the soft tracks (ST) that come from the decay of the corresponding chargino.

These findings suggest that the 3 TeV MuC is not only a stage towards the 10 TeV machine, but it is also a powerful discovery machine.

Outline

1. Introduction

- Pillars of the Energy Frontier
- MuC strong candidate for both

2. Minimal WIMPs

- Properties
- Projections

3. Soft Tracks

- Signal Regions
- Background Determination

4. Results

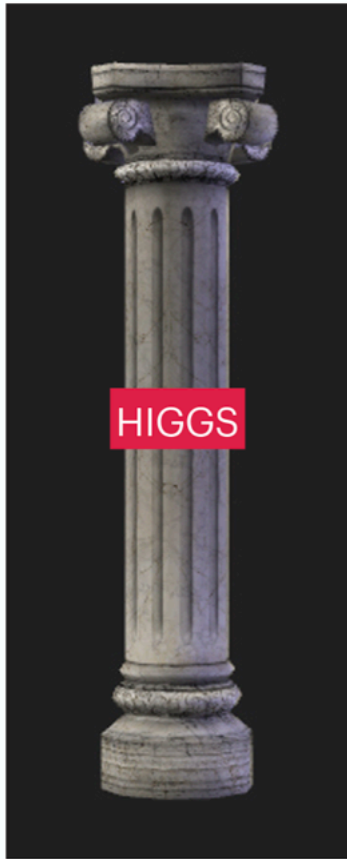
- The Importance of the 3TeV MuC!

5. Discussion/Summary

1. Introduction

- Pillars for the Energy Frontier:

Foundational Physics Cases



Precision



Energy

Higgs:

*Is there a more fundamental description of EWSB?
What mechanism sets the scale and stabilizes the
Higgs mass?*

...

BSM:

*What is the nature of Dark Matter?
What is the mechanism for Baryogenesis?
What is the mechanism for neutrino masses?
The unknown! How can nature surprise us?*

...

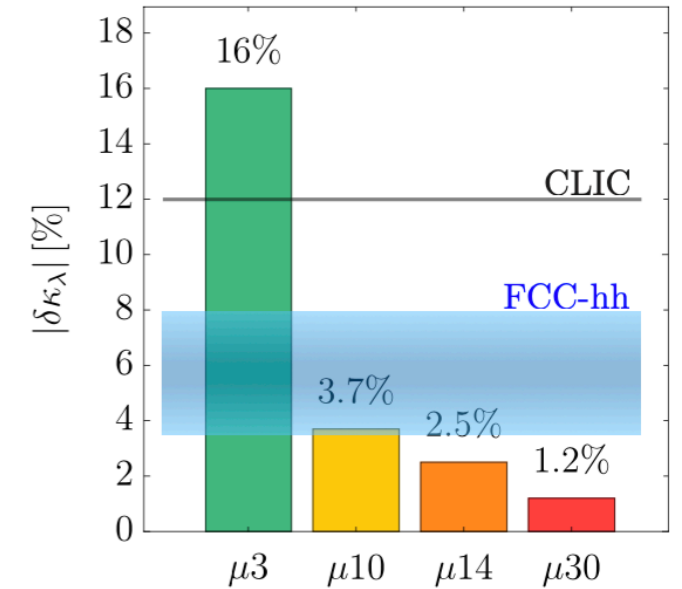
From Patrick Meade's talks!

1. Introduction

- MuC strong candidate for both:

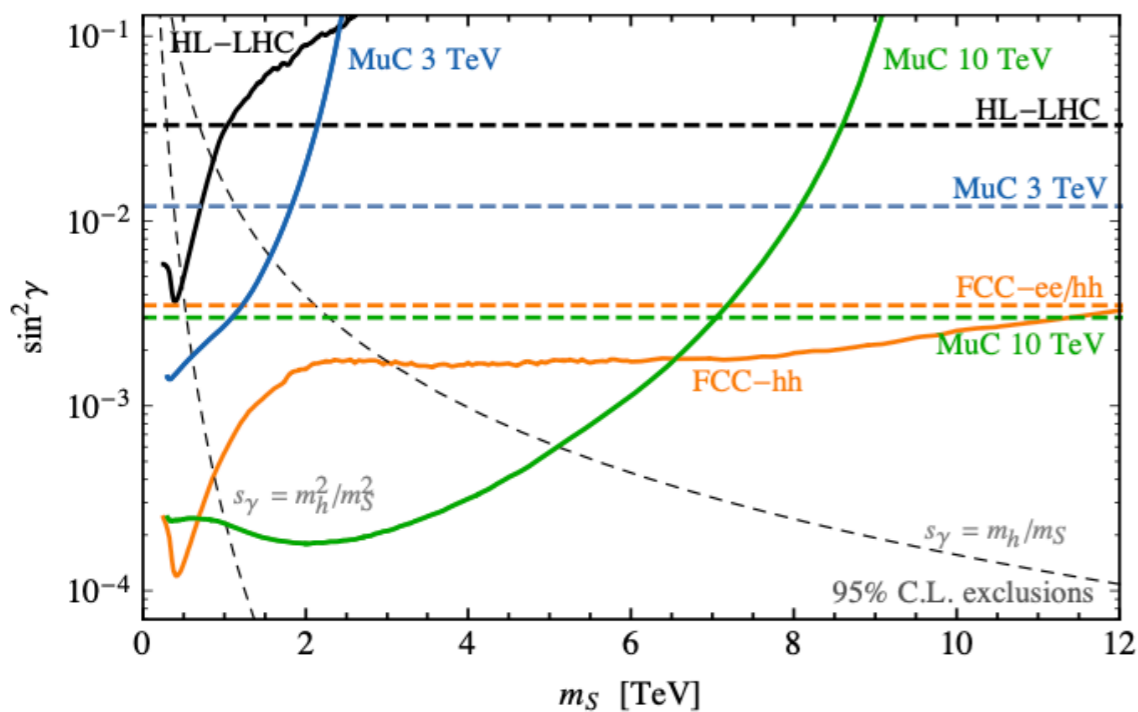
Higgs/Precision

$\kappa-0$ fit	HL-LHC	LHeC	HE-LHC S2 S2'	ILC 250 500 1000	CLIC 380 1500 3000	CEPC	FCC-ee 240 365	FCC-ee/ eh/hh	$\mu^+\mu^-$ 10000
κ_W [%]	1.7	0.75	1.4 0.98	1.8 0.29 0.24	0.86 0.16 0.11	1.3	1.3 0.43	0.14	0.06
κ_Z [%]	1.5	1.2	1.3 0.9	0.29 0.23 0.22	0.5 0.26 0.23	0.14	0.20 0.17	0.12	0.23
κ_g [%]	2.3	3.6	1.9 1.2	2.3 0.97 0.66	2.5 1.3 0.9	1.5	1.7 1.0	0.49	0.15
κ_γ [%]	1.9	7.6	1.6 1.2	6.7 3.4 1.9	98* 5.0 2.2	3.7	4.7 3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	—	5.7 3.8	99* 86* 85*	120* 15 6.9	8.2	81* 75*	0.69	1.0
κ_c [%]	—	4.1	— —	2.5 1.3 0.9	4.3 1.8 1.4	2.2	1.8 1.3	0.95	0.89
κ_t [%]	3.3	—	2.8 1.7	— 6.9 1.6	— — 2.7	—	— —	1.0	6.0
κ_b [%]	3.6	2.1	3.2 2.3	1.8 0.58 0.48	1.9 0.46 0.37	1.2	1.3 0.67	0.43	0.16
κ_μ [%]	4.6	—	2.5 1.7	15 9.4 6.2	320* 13 5.8	8.9	10 8.9	0.41	2.0
κ_τ [%]	1.9	3.3	1.5 1.1	1.9 0.70 0.57	3.0 1.3 0.88	1.3	1.4 0.73	0.44	0.31

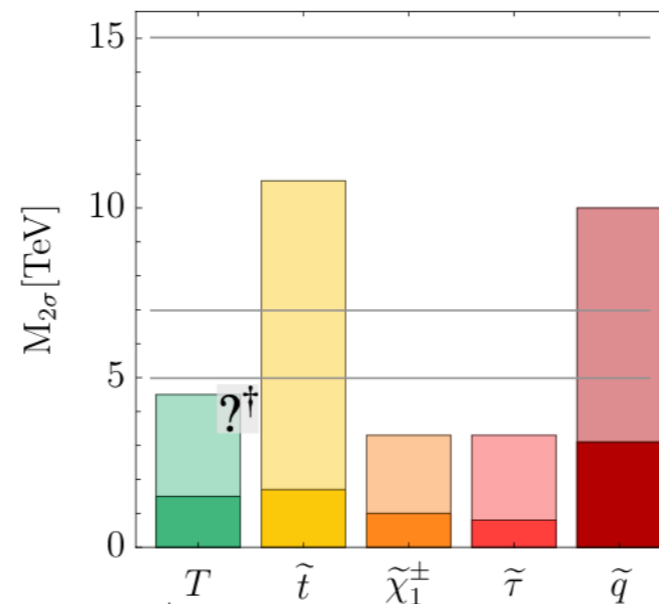


H. Al Ali et al., Muon Smasher's guide + Delphes

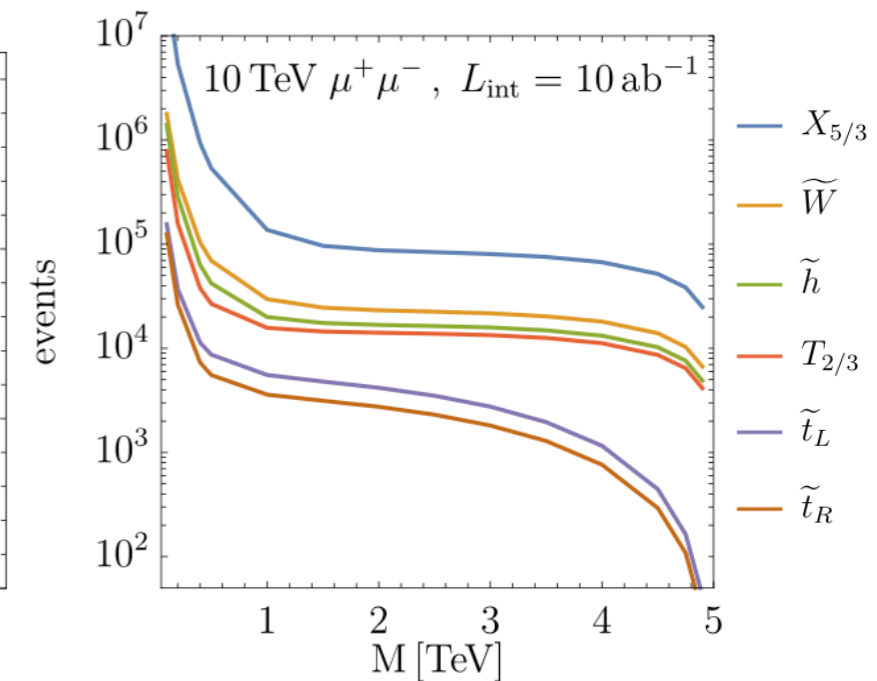
BSM/Unknown



H. Al Ali et al., Muon Smasher's guide



D. Buttazzo,
R. Franceschini,
A. Wulzer,
JHEP 05 (2021) 219



R. K. Ellis et al.,
arXiv:1910.11775

2. Minimal WIMPs



Dark Matter



Hierarchy
Problem



Neutrino
Mass



Baryogenesis

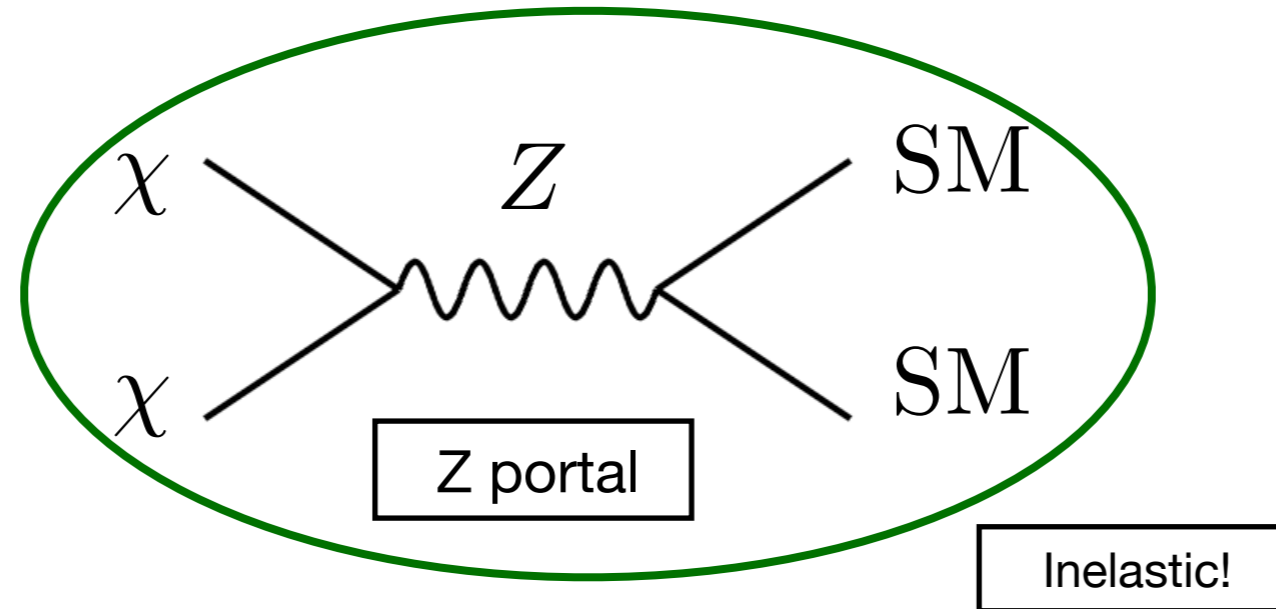


**Minimal
WIMPs**

...

2. Minimal WIMPs

- Properties:



EW multiplets

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\chi_{\tilde{H}} = \begin{pmatrix} \chi_{\tilde{H}}^+ \\ \chi_{\tilde{H}}^0 \\ \chi_{\tilde{H}}^- \end{pmatrix}$$

$(\mathbf{1}, \mathbf{2}, 1/2)$
Higgsino-like

$$\chi_{\tilde{W}} = \begin{pmatrix} \chi_{\tilde{W}}^+ \\ \chi_{\tilde{W}}^0 \\ \chi_{\tilde{W}}^- \end{pmatrix}$$

$(\mathbf{1}, \mathbf{3}, 0)$
Wino-like

Neutral component = DM

2. Minimal WIMPs

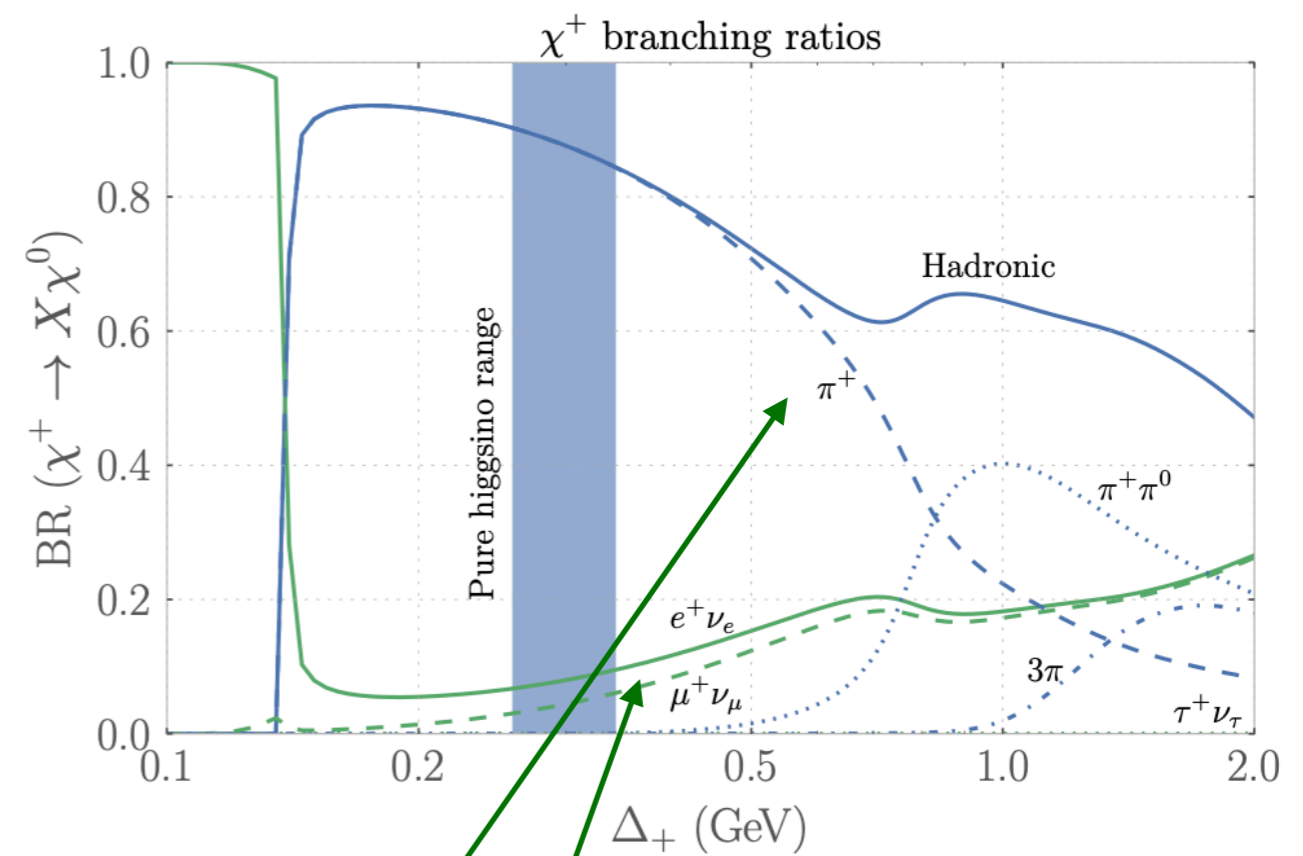
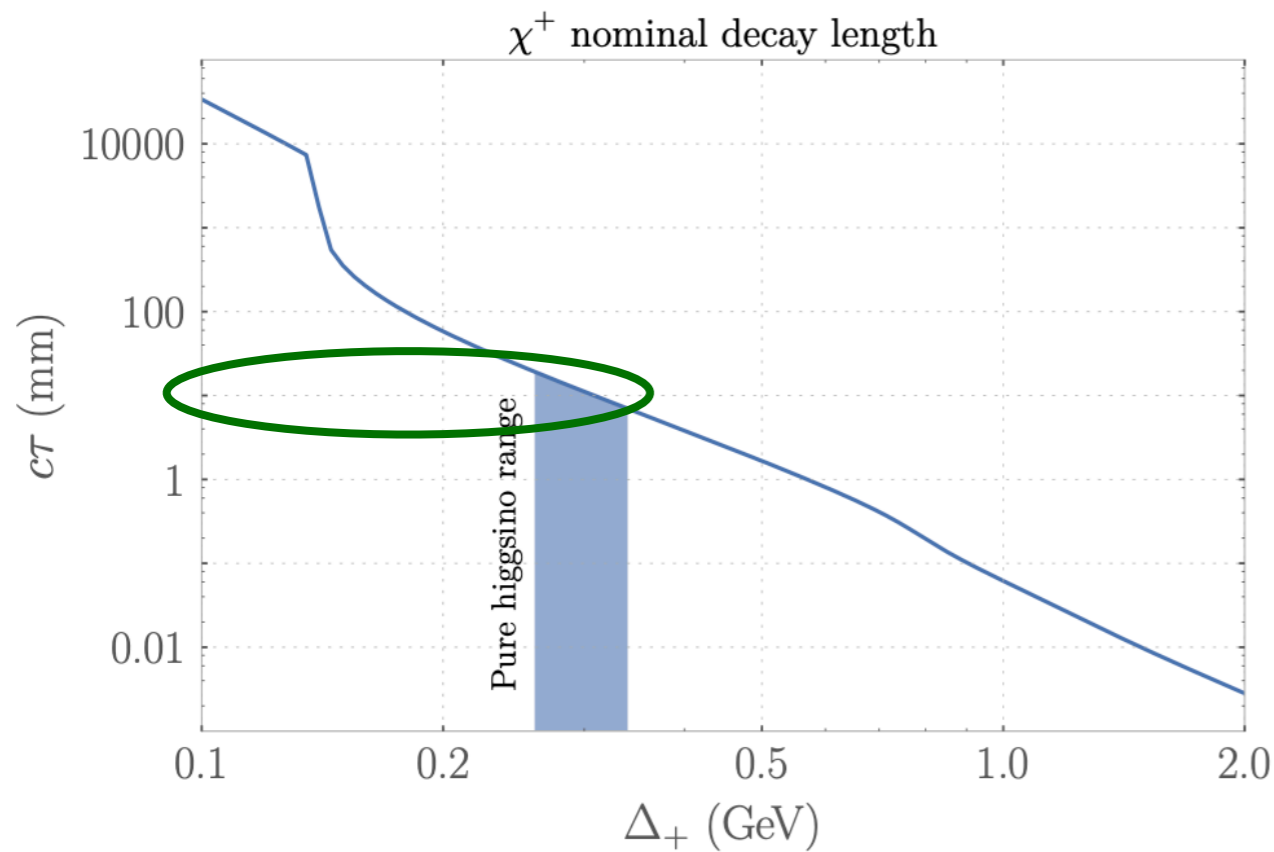
- Properties:

$$\Delta m = m_{\chi^+} - m_{\chi^0} > 0$$

Small mass splitting
(from loops)



Long lifetime
Disappearing Tracks
Soft Tracks



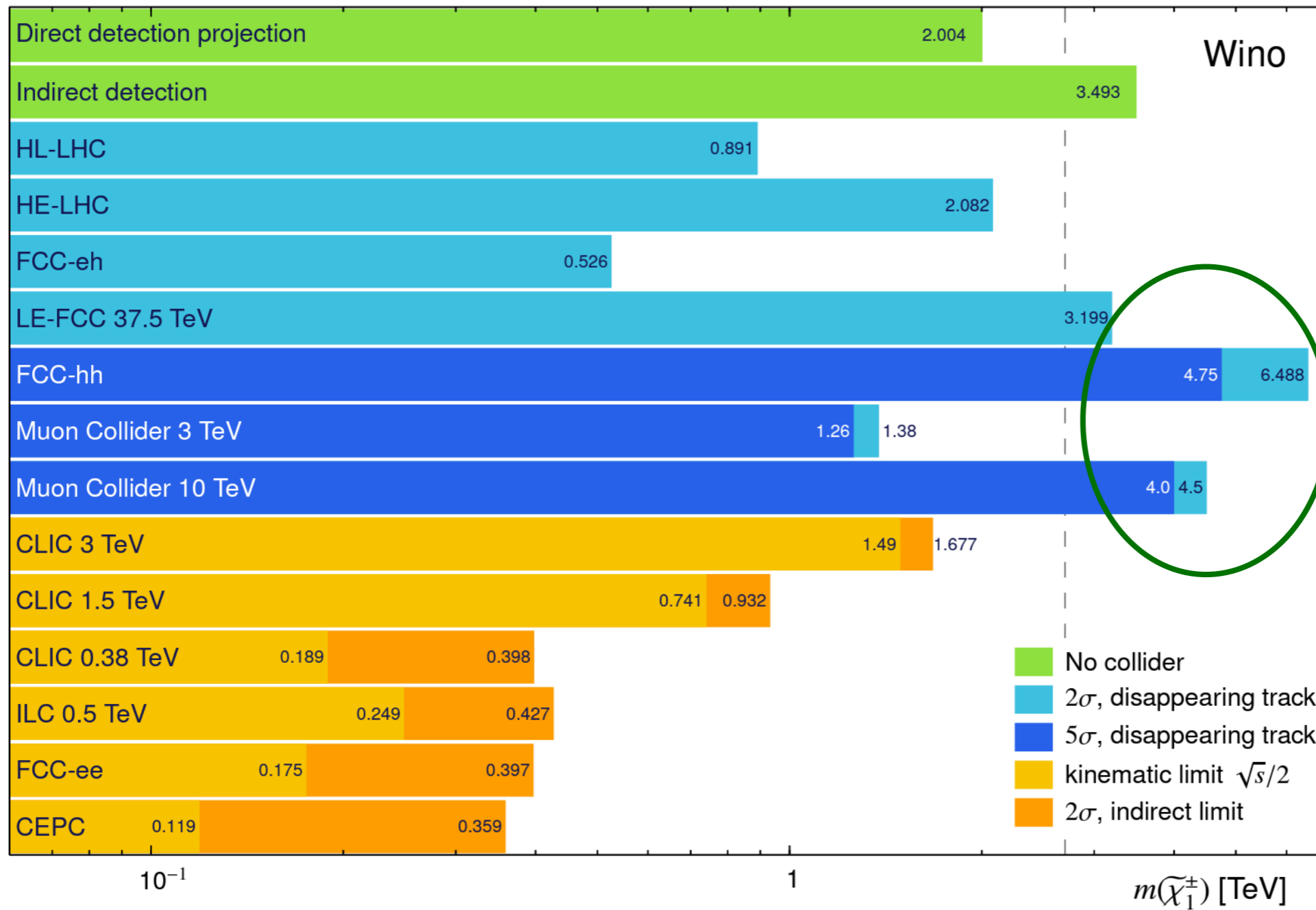
Soft pions
Soft muons
Soft electrons = Soft Tracks (ST)

R. Mahbubani, P. Schwaller, J. Zurita, JHEP 06 (2017) 119

2. Minimal WIMPs

- Projections:

RC, F. Meloni, R. Simoniello, J. Zurita, JHEP 06 (2021) 133

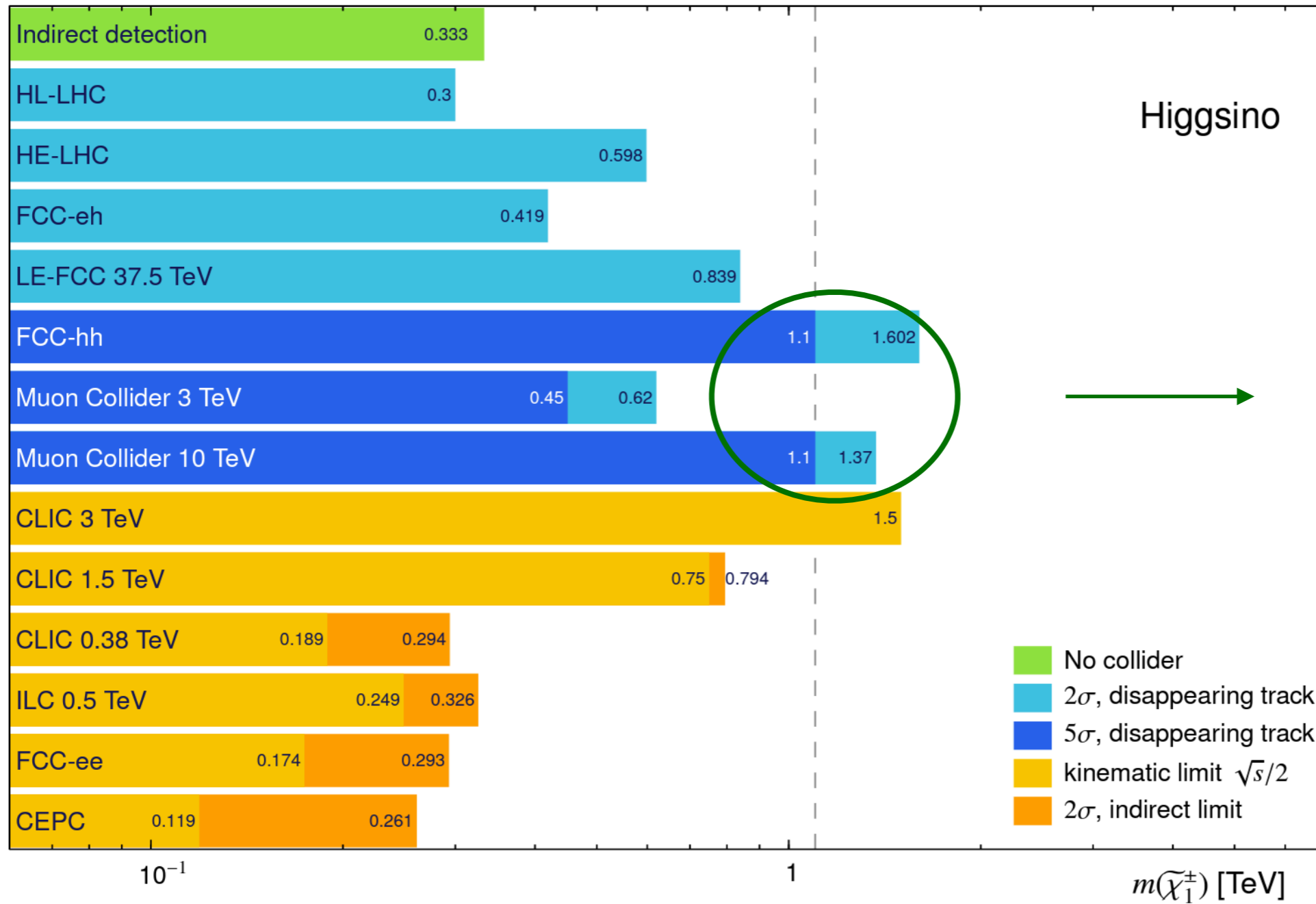


Discovery potential from DT

2. Minimal WIMPs

- Projections:

RC, F. Meloni, R. Simoniello, J. Zurita, JHEP 06 (2021) 133



Not clear discovery potential...

Outline

1. Introduction

- Pillars of the Energy Frontier
- MuC strong candidate for both

2. Minimal WIMPs

- Properties
- Projections

3. Soft Tracks

- **Signal Regions**
- **Background Determination**

4. Results

- The Importance of the 3TeV MuC!

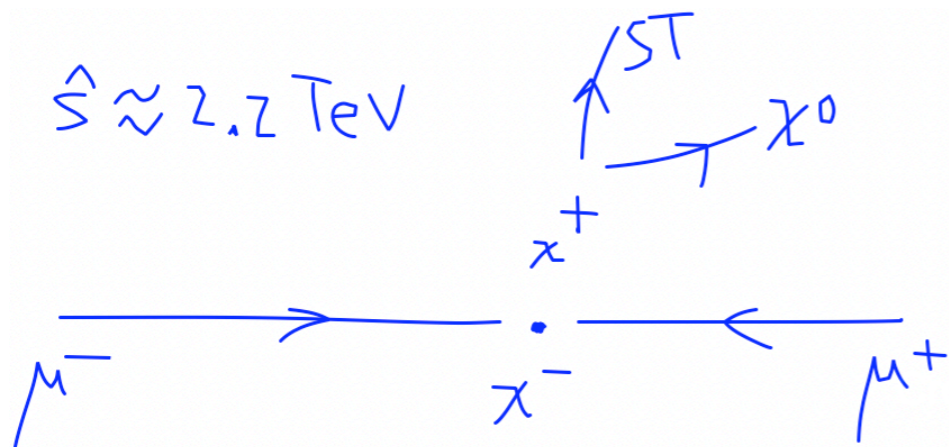
5. Discussion/Summary

3. Soft Tracks

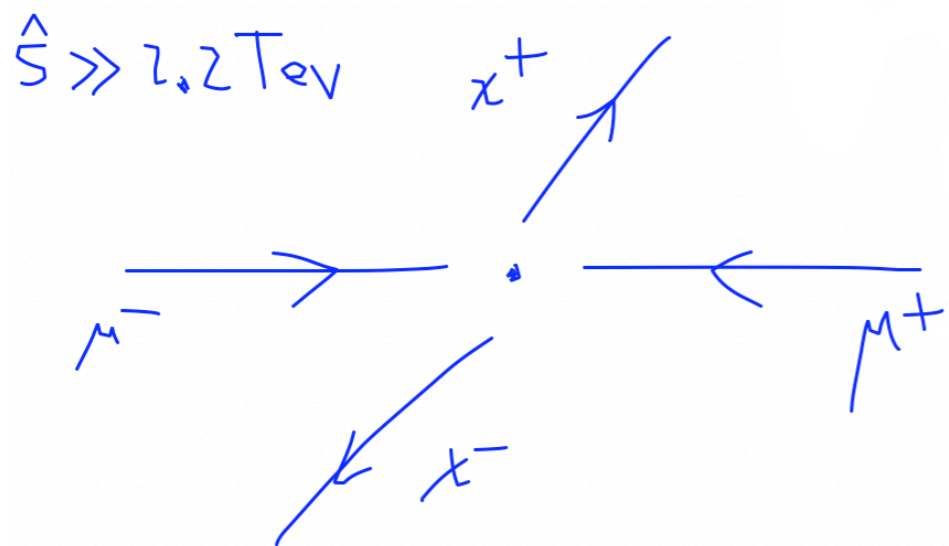
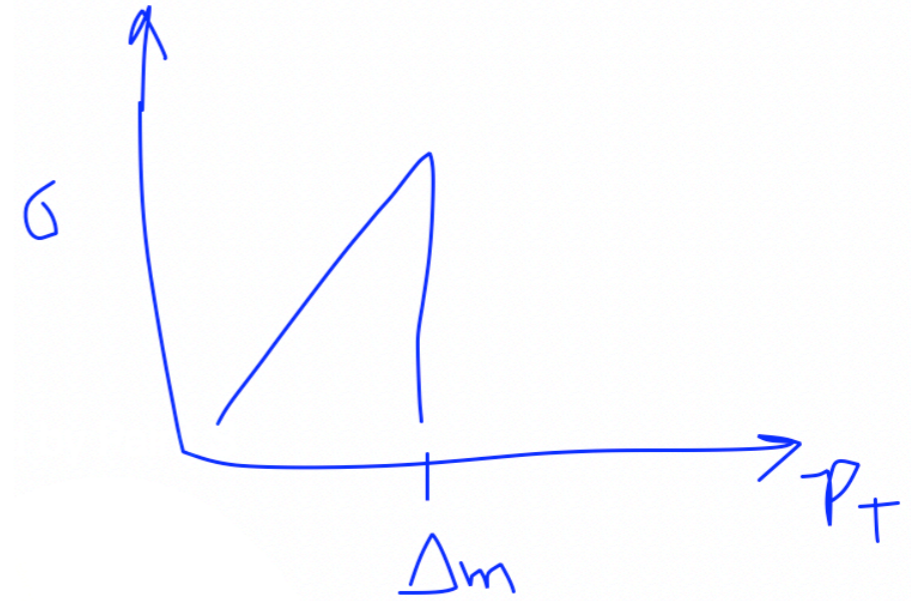
Thermal Higgsino

Very small gap!

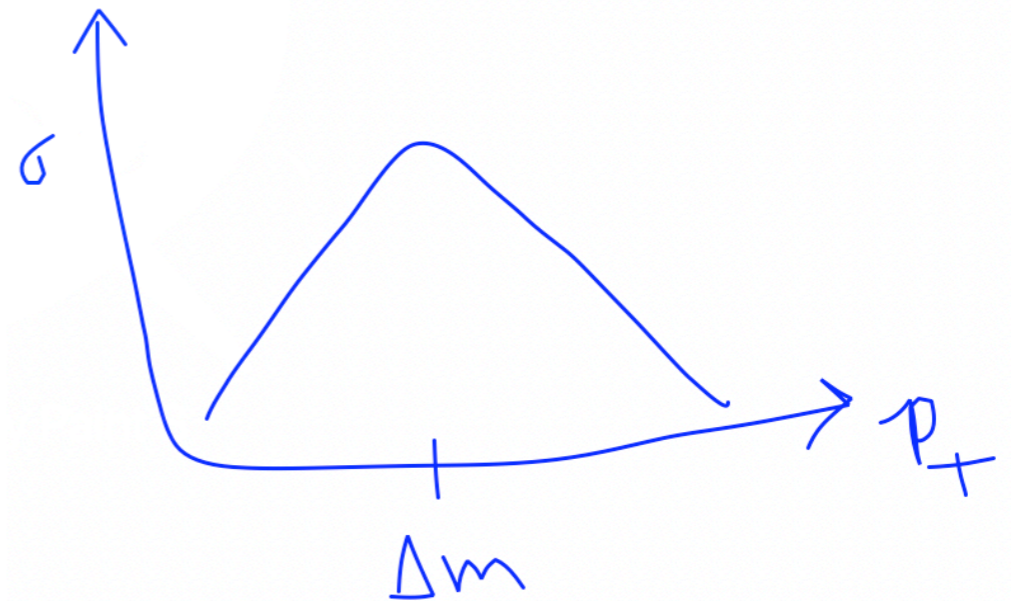
$$\Delta m \sim 0.3 \text{ GeV}$$



Threshold production



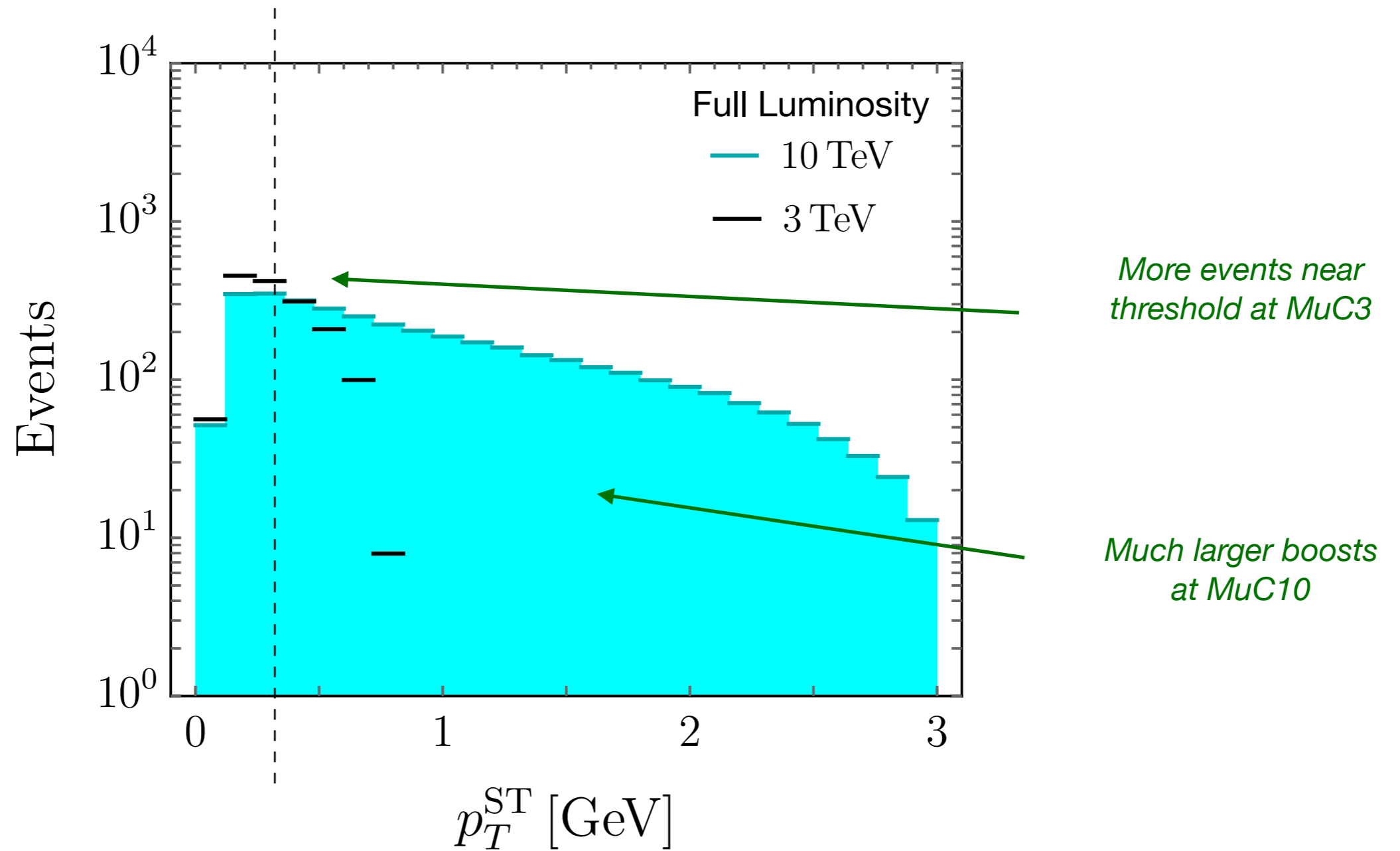
Boosted production



3. Soft Tracks

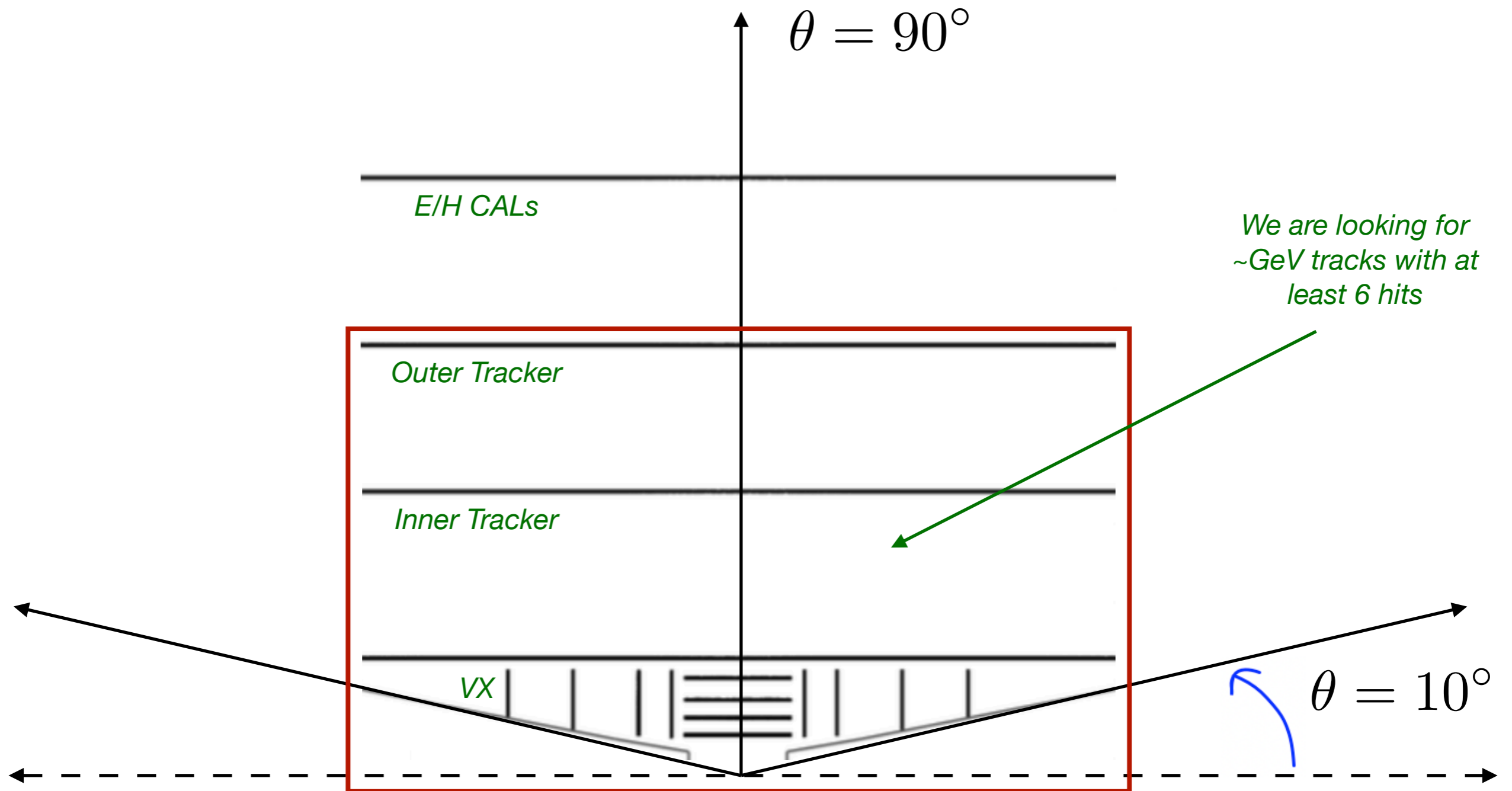
Thermal Higgsino

$\Delta m \sim 0.3 \text{ GeV}$



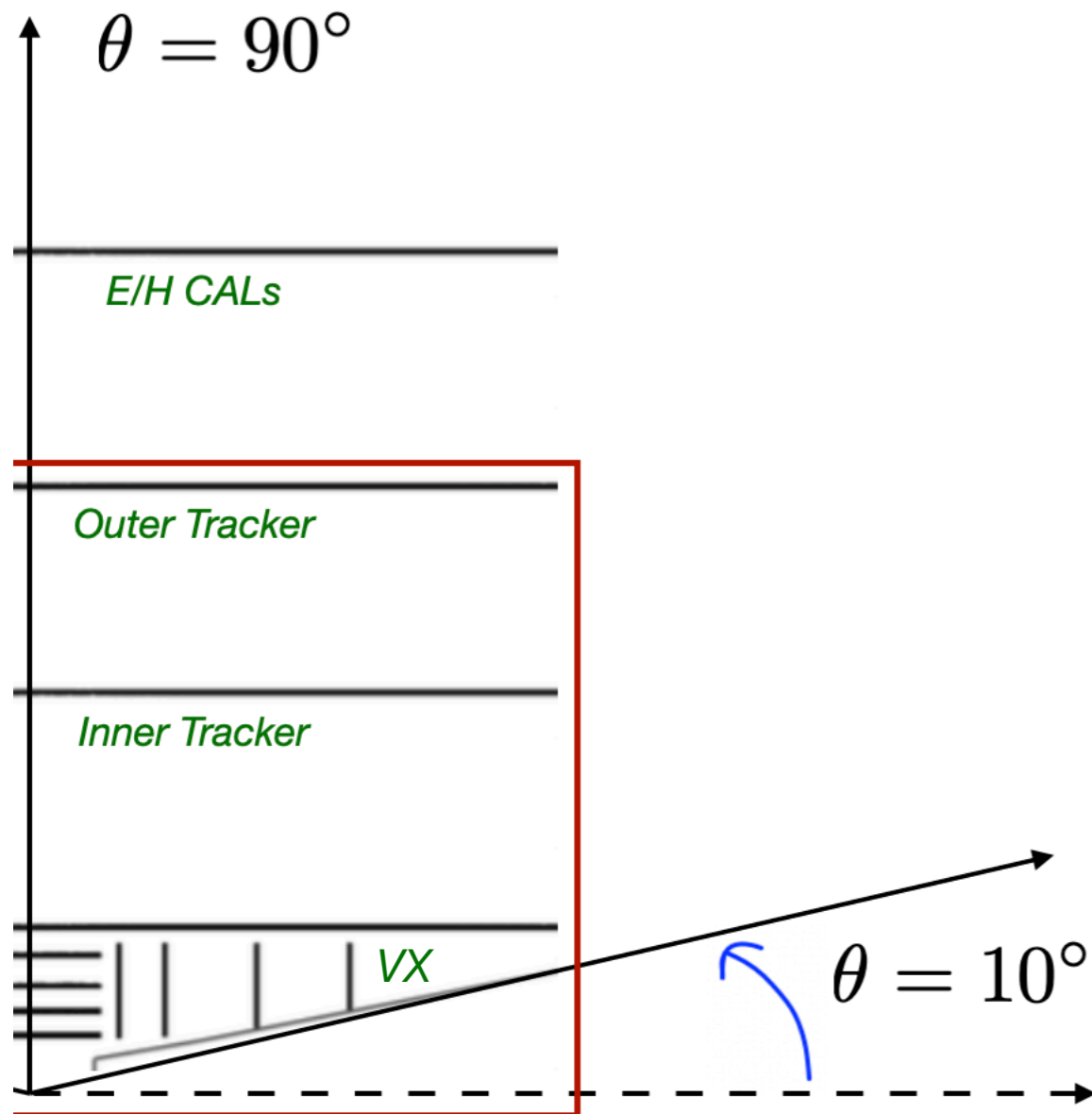
3. Soft Tracks

- Definition of a ST:



3. Soft Tracks

- Definition of a ST:



Thermal Higgsino

Soft Track

ℓ^\pm (Leptons) h^\pm (Hadrons)

$10^\circ < \theta < 170^\circ$

A priori $0.1 < p_T < 1 \text{ GeV}$
 $0.1 < p_T < 3 \text{ GeV}$

MuC3
 MuC10

Heavy Neutrals

$E > 10 \text{ GeV}$

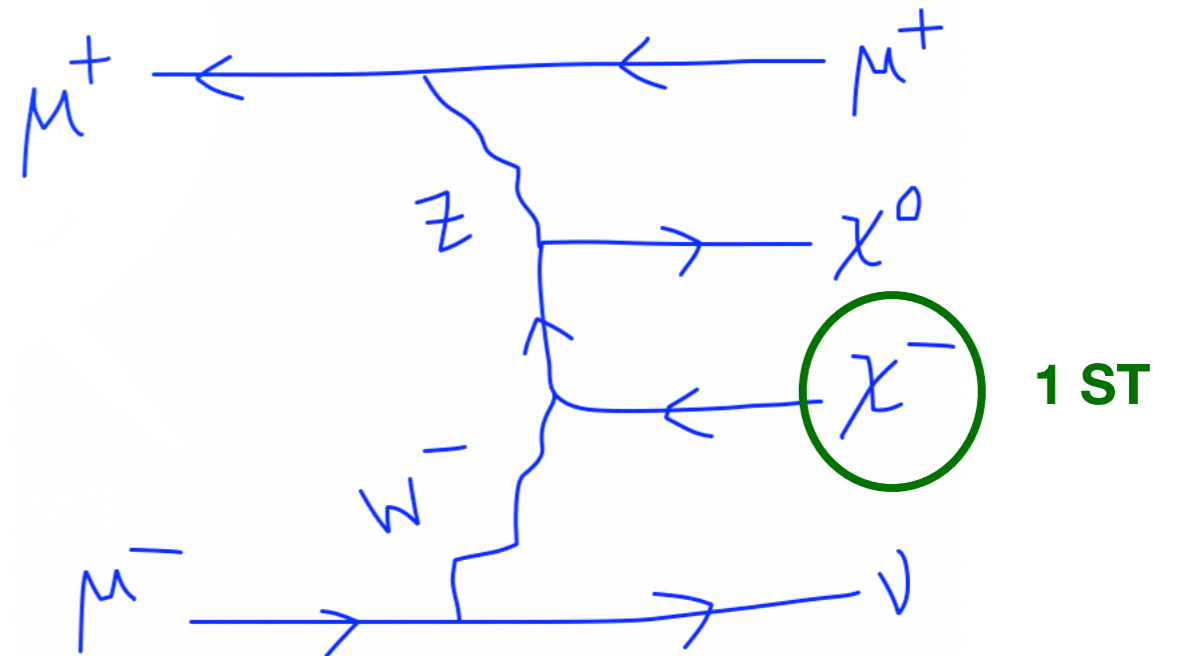
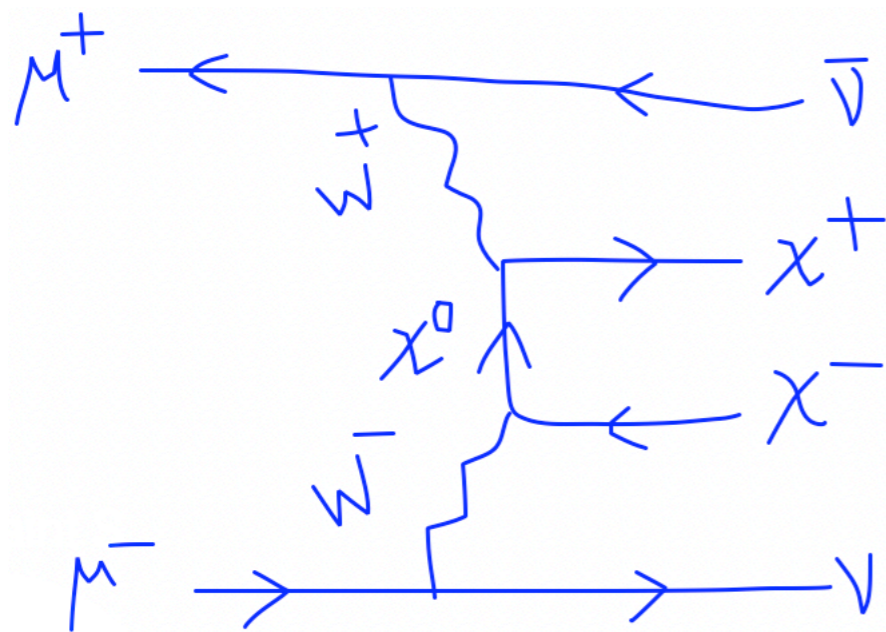
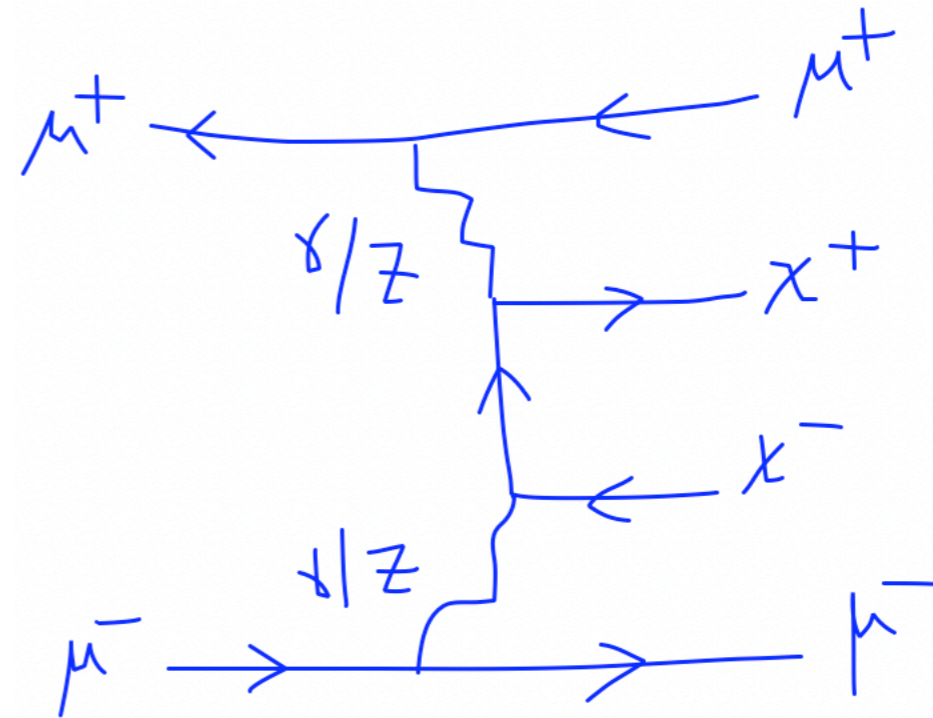
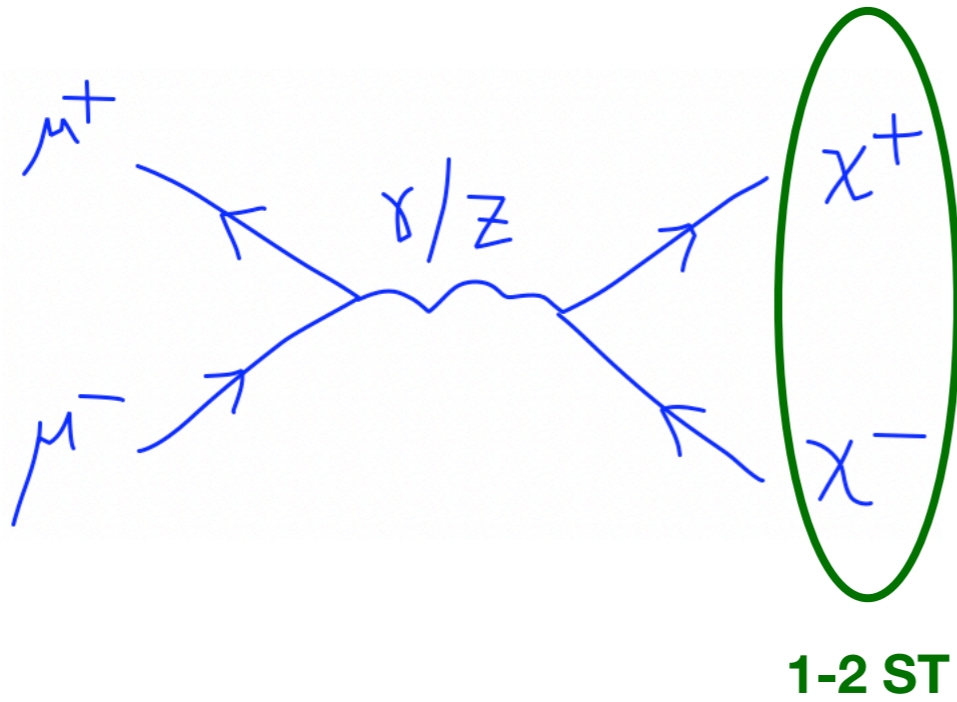
Photons

$10^\circ < \theta < 170^\circ$

$p_T > 10 \text{ GeV}$

3. Soft Tracks

- Signal Regions:



3. Soft Tracks

- Signal Regions:

Thermal Higgsino

MuC 3 TeV

1ST 0 γ 14%	1ST 1 γ 2%
2ST 0 γ 75%	2ST 1 γ 9%
$\sigma_T = 12.53(3) \text{ fb}$	

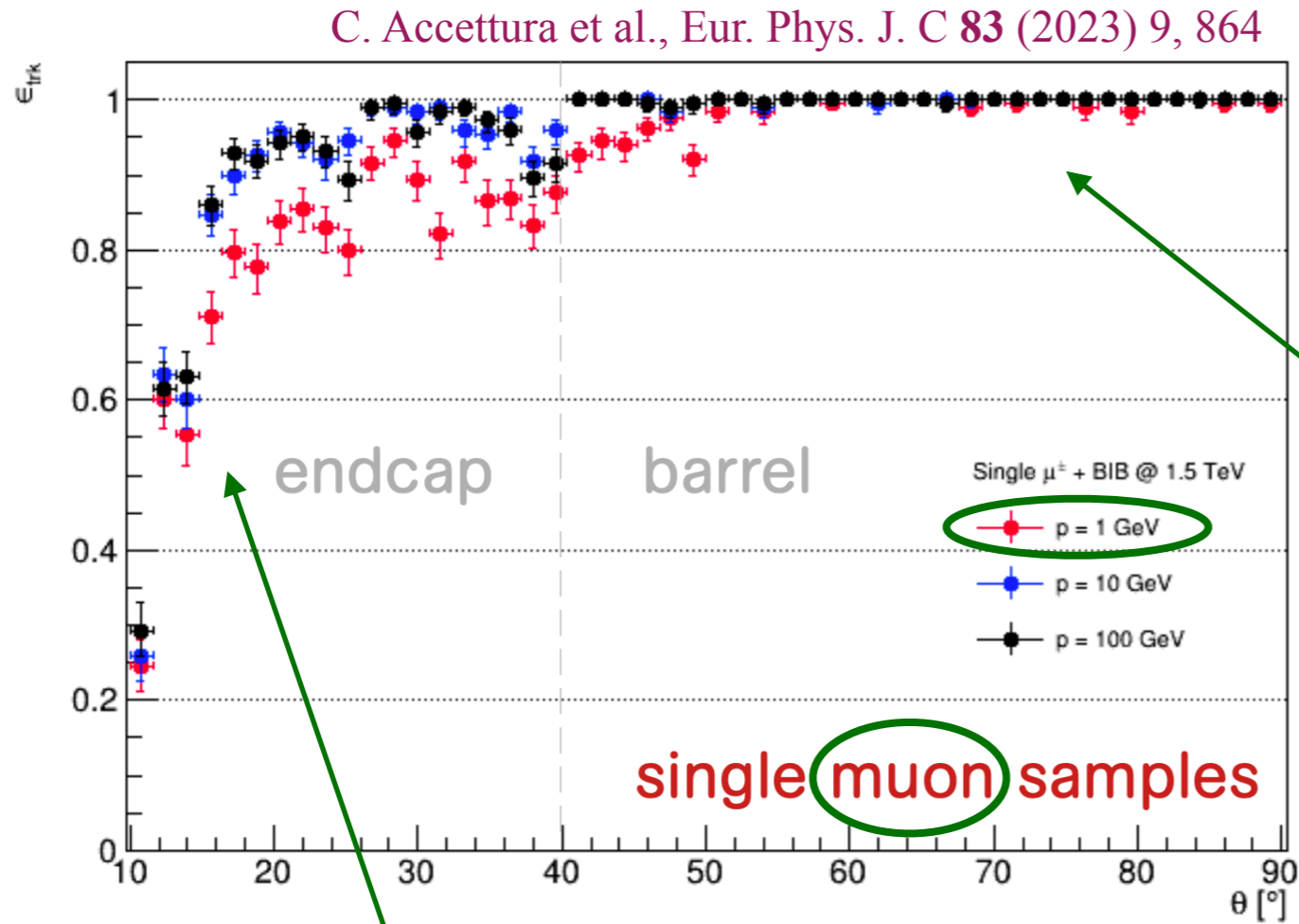
MuC 10 TeV

1ST 0 γ 7%	1ST 1 γ 2%
2ST 0 γ 65%	2ST 1 γ 20%
$\sigma_T = 1.7996(36) \text{ fb}$	

*About 1k signal events
in this signal region*

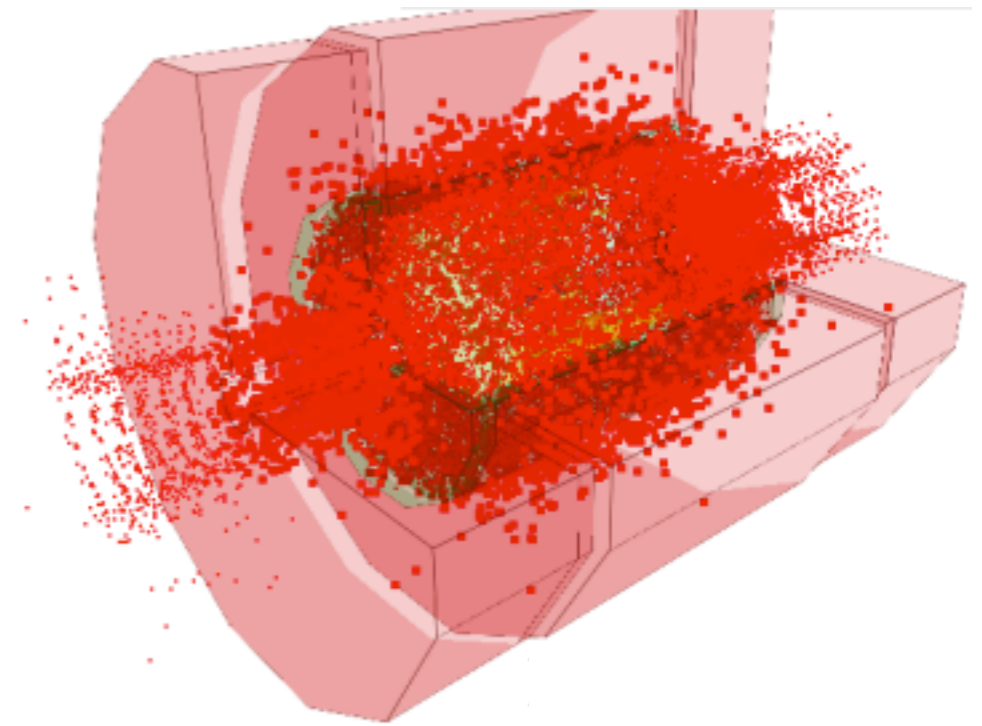
3. Soft Tracks

- Backgrounds: BIB



Forward/backward angular regions:

Large probability of missing a track immersed in the BIB

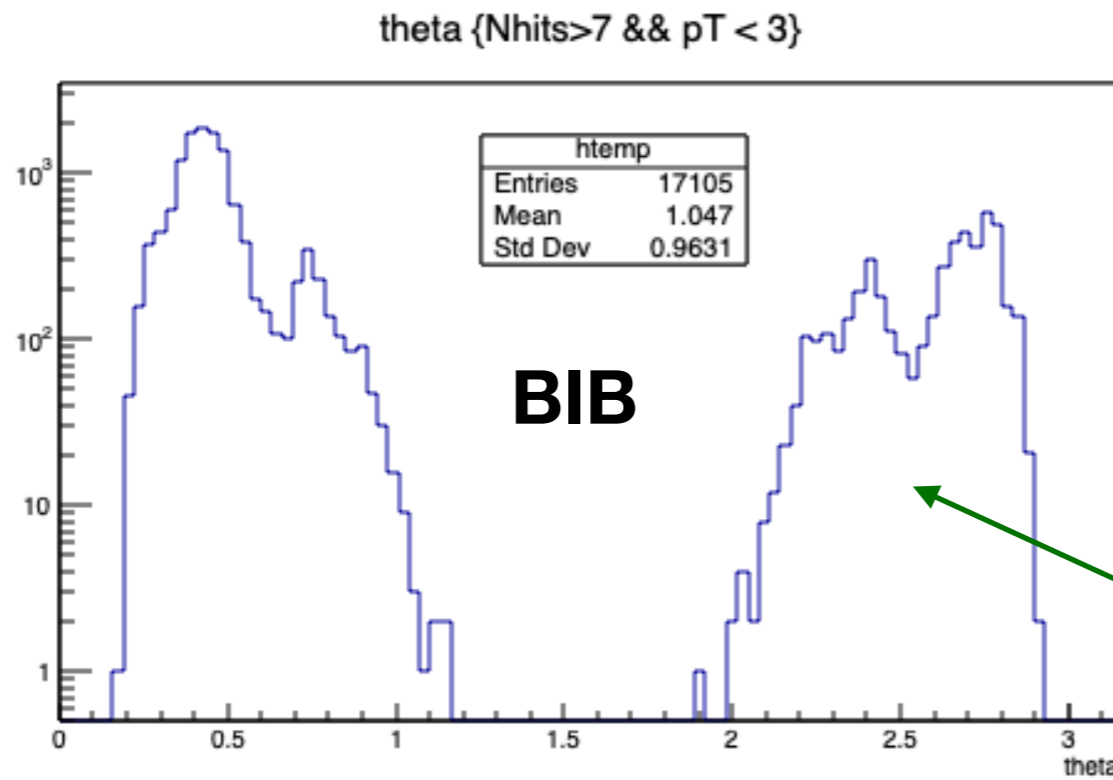
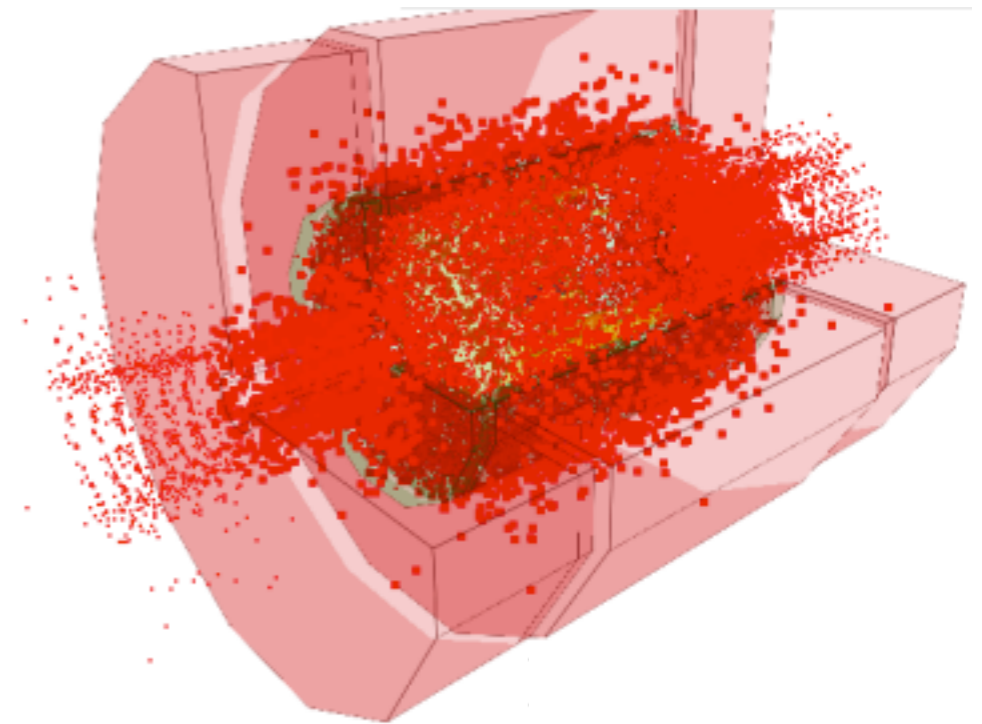


Central angular region:

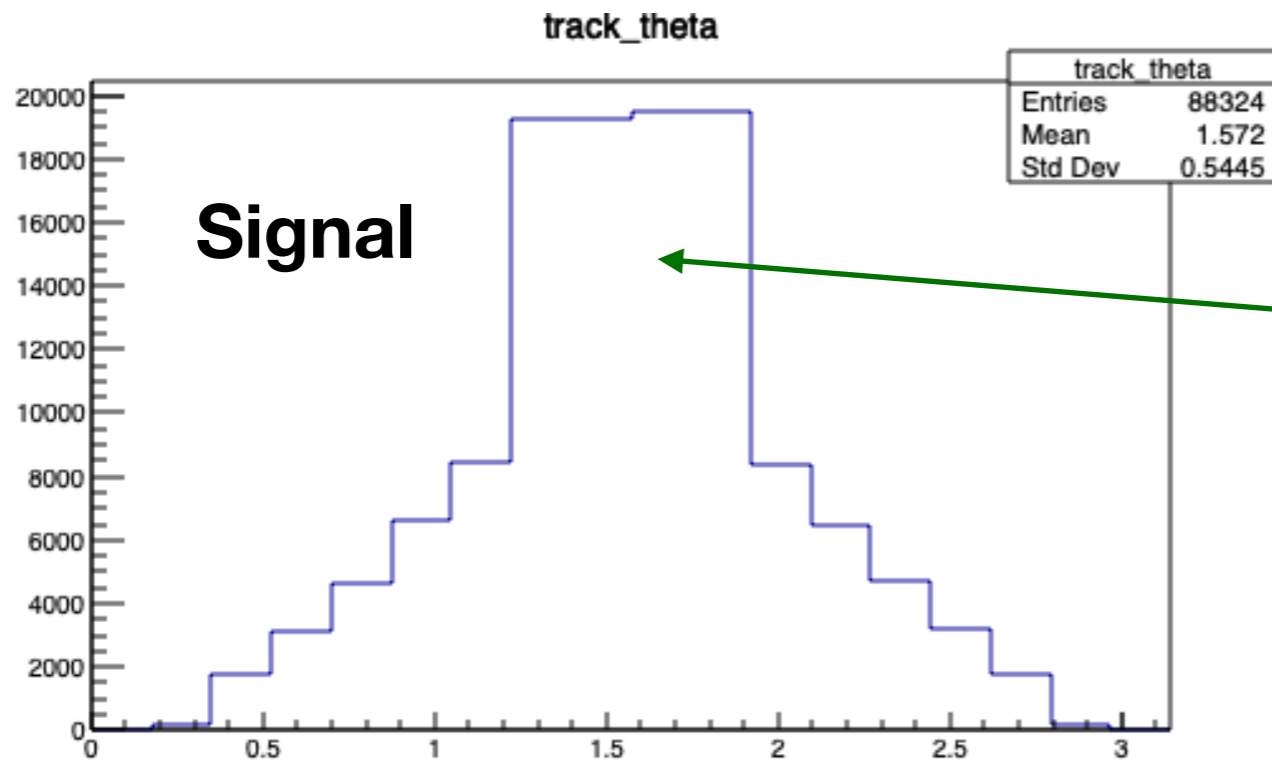
Small probability of missing a track immersed in the BIB

3. Soft Tracks

- Backgrounds: BIB



The BIB wants to be forward/backward

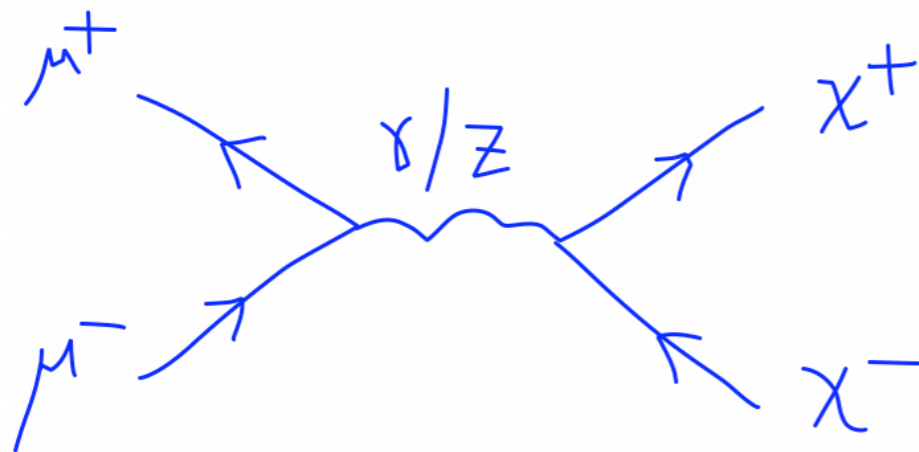


The signal wants to be central

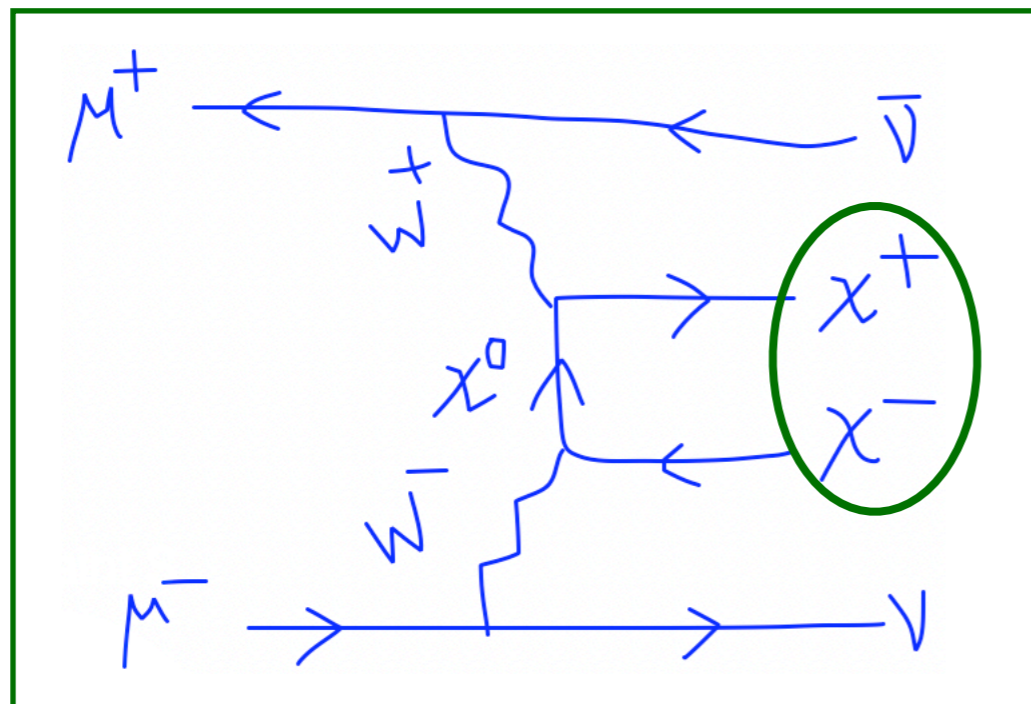
3. Soft Tracks

- Backgrounds:

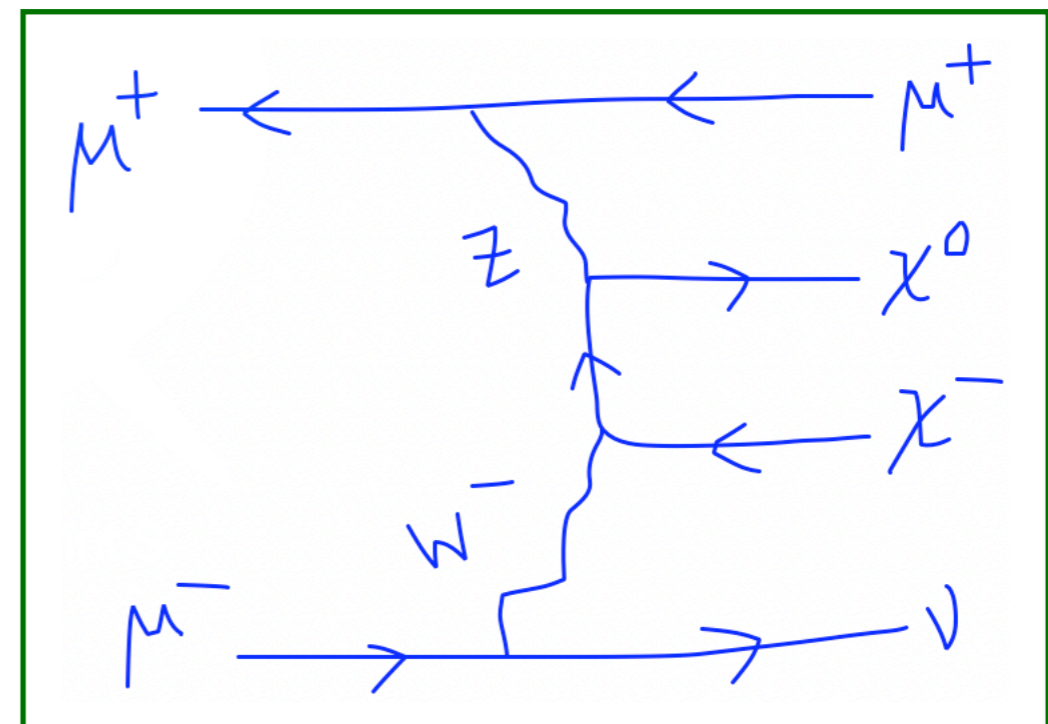
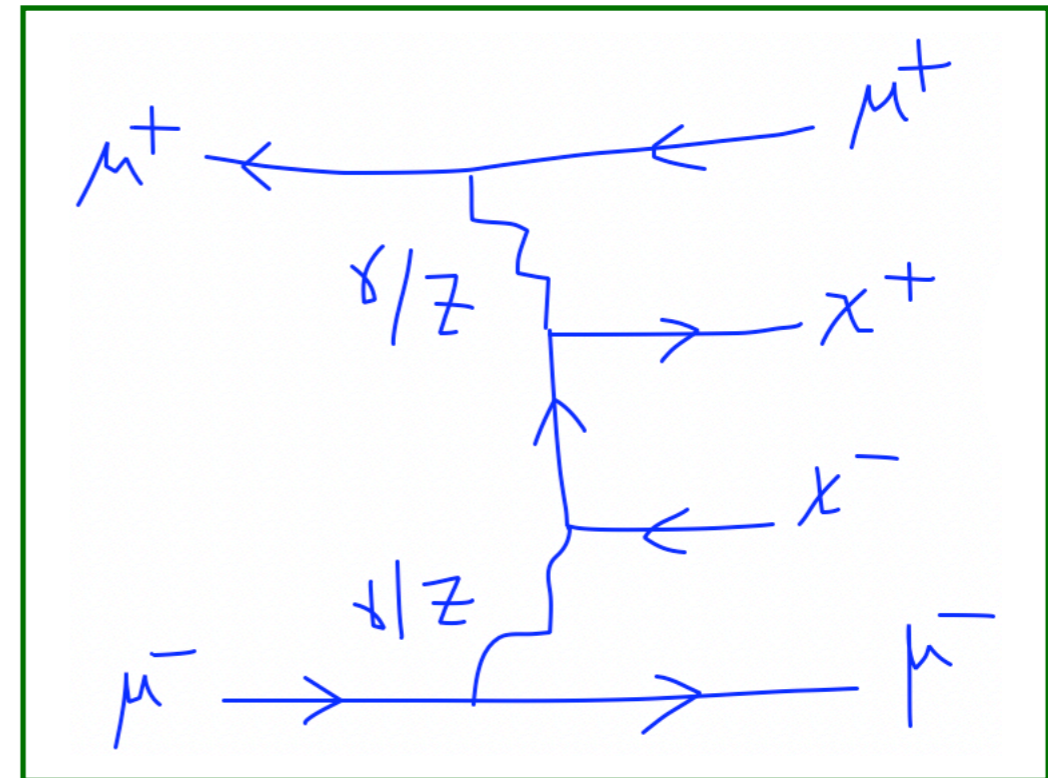
$$\chi^+ \chi^- \longrightarrow \tau^+ \tau^- \ell^+ \ell^- jj$$



Dominant backgrounds!

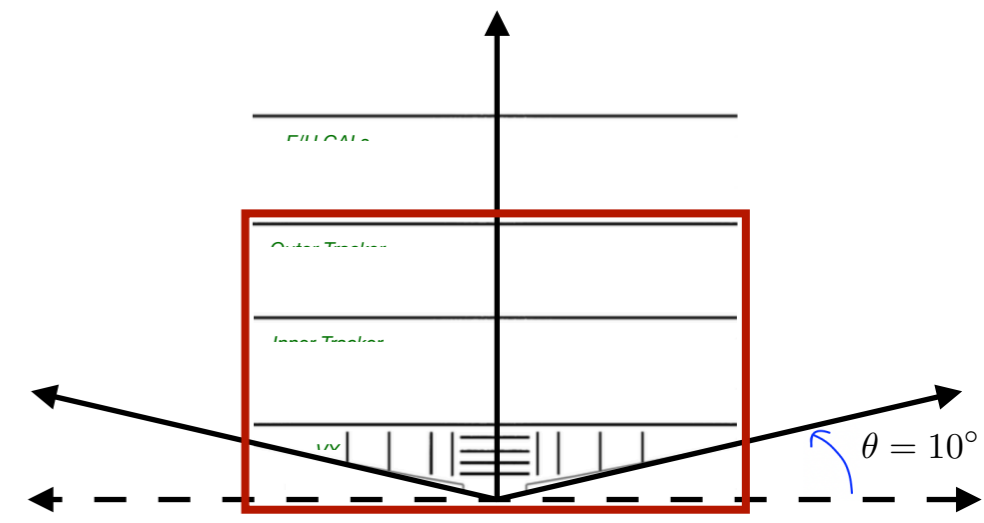


Large energy loss in the forward region!

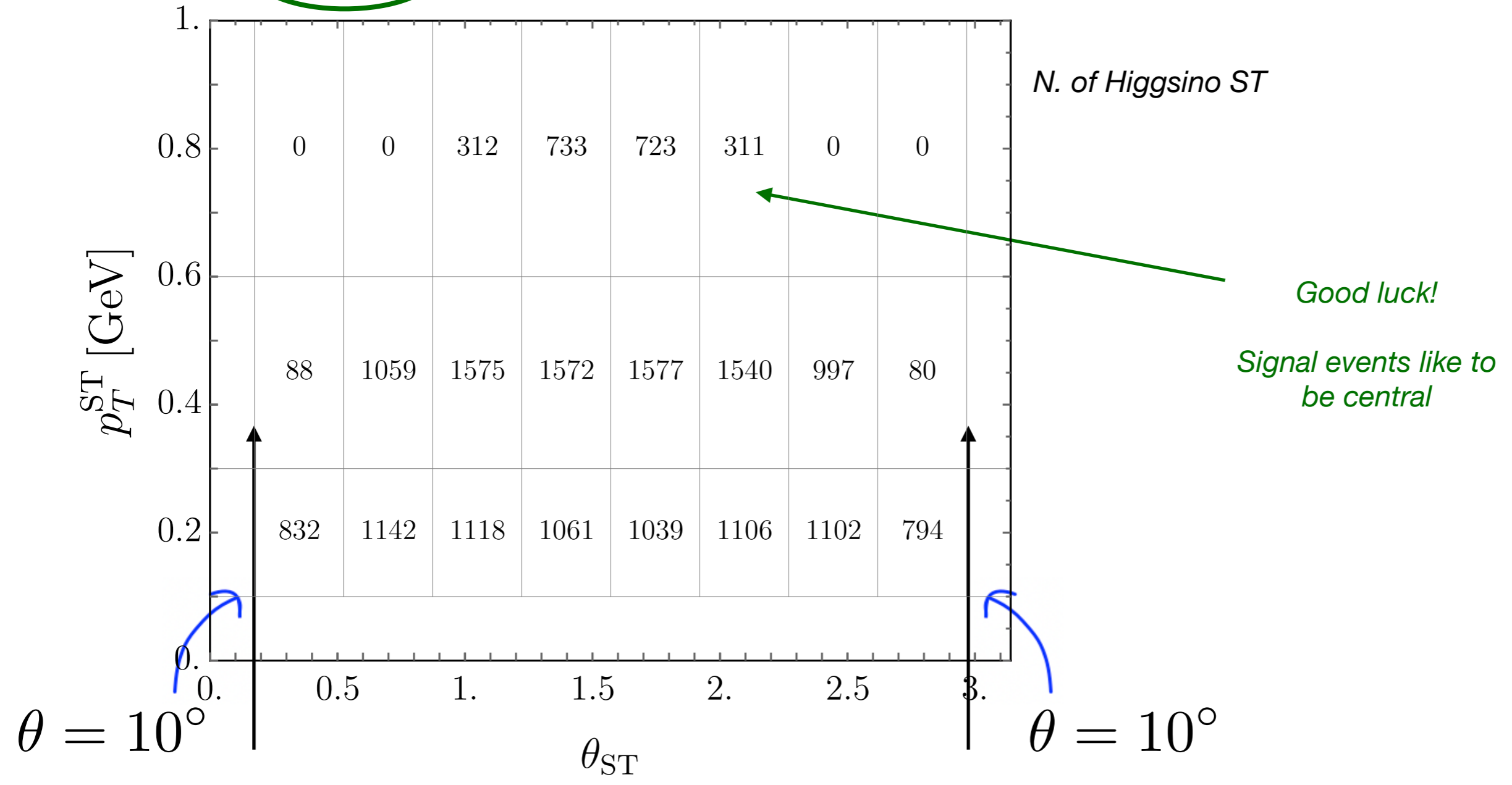


3. Soft Tracks

- Backgrounds:

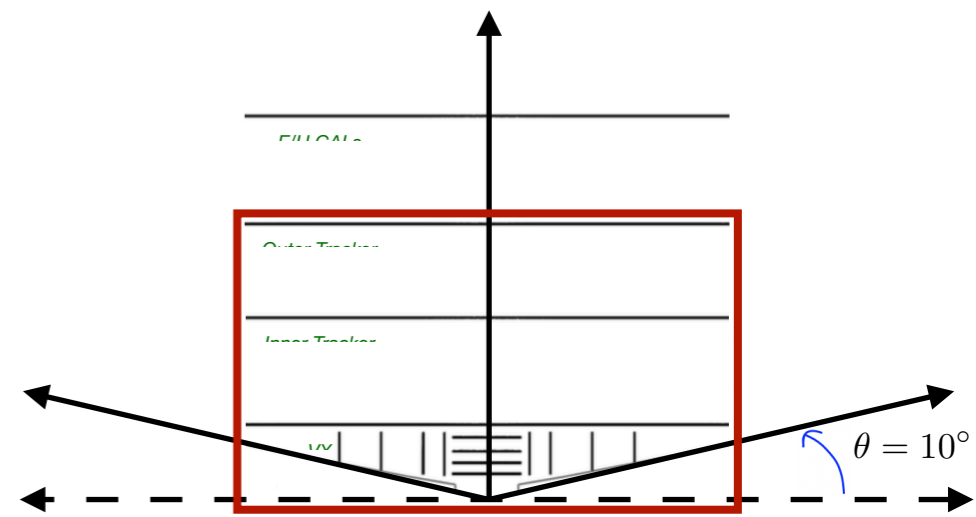


2ST0 γ , MuC3, 1ab $^{-1}$, Higgsinos

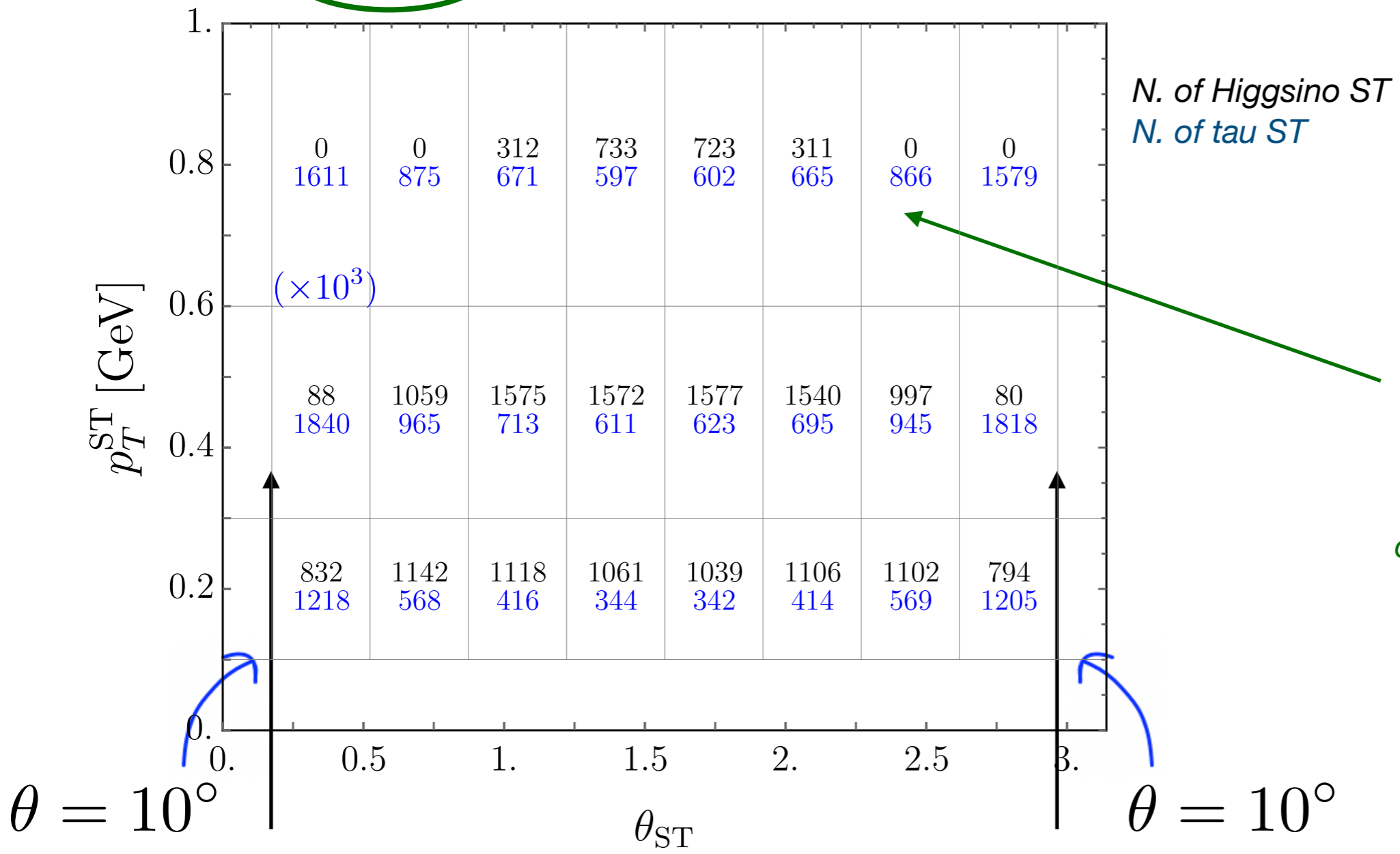


3. Soft Tracks

- Backgrounds:



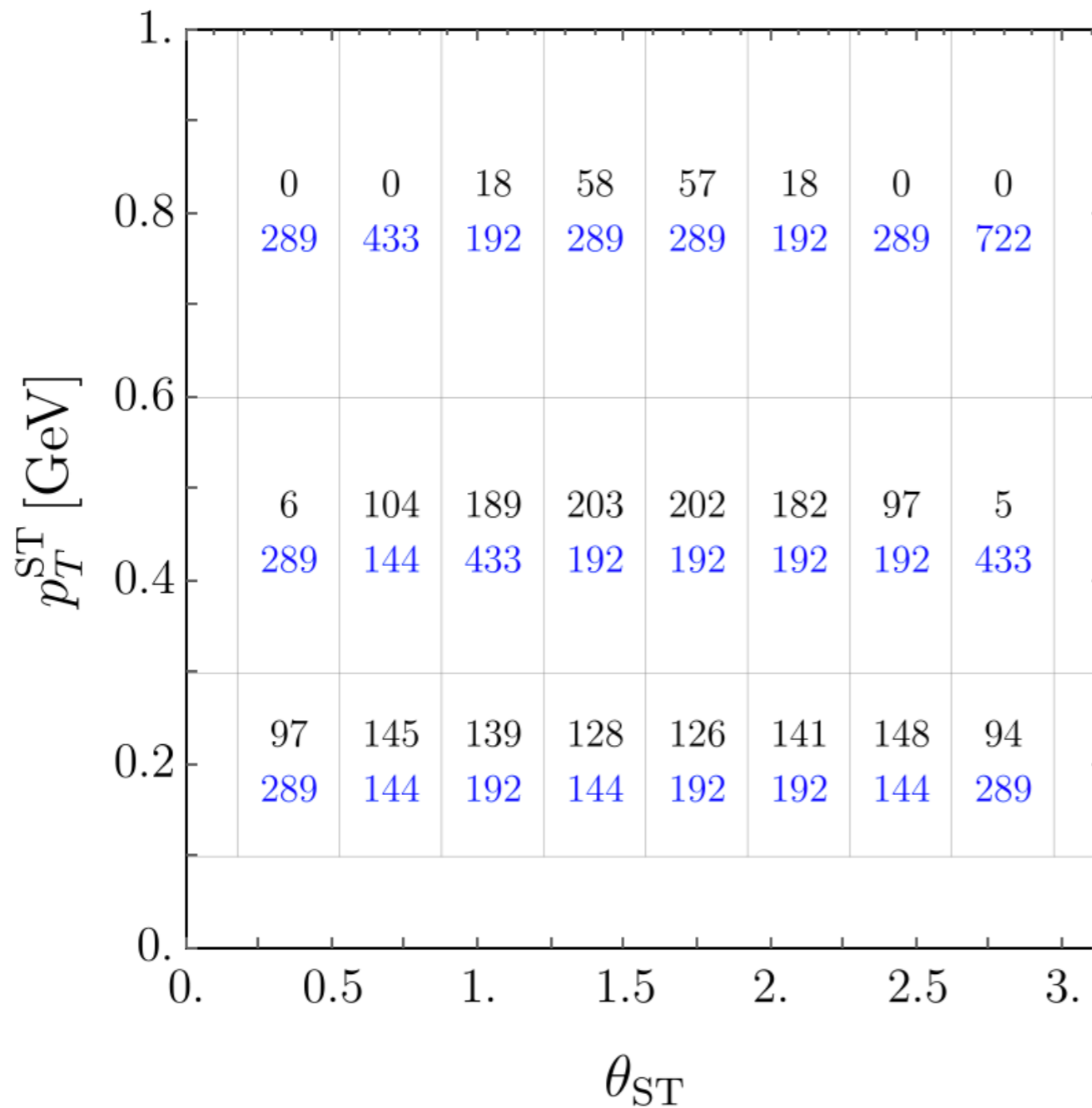
2ST0 γ , MuC3, 1ab⁻¹, Higgsinos



Bad luck!
The signal region with more events is overwhelmed by the background!

3. Soft Tracks

- Backgrounds:



N. of Higgsino ST
N. of tau ST

MuC3, 1ab^{-1}

2ST1 γ , Higgsinos

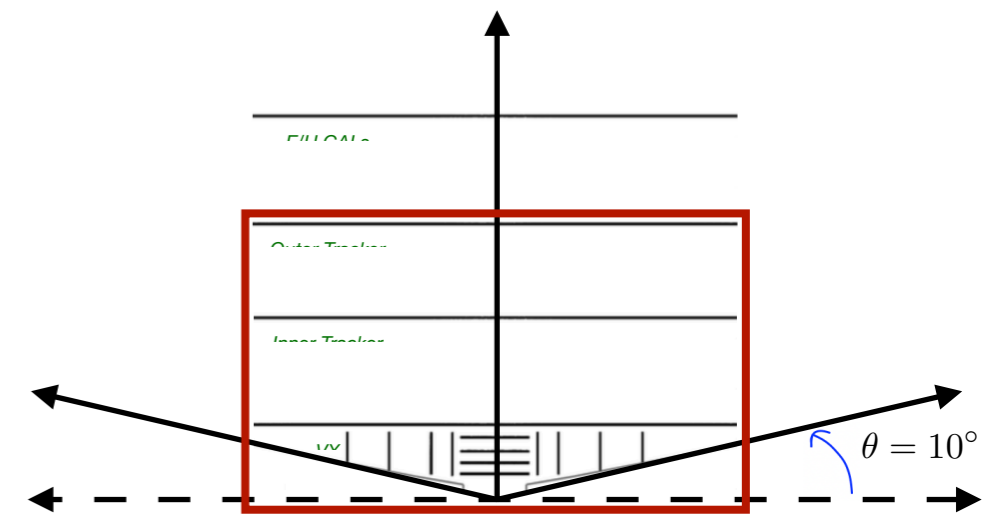
$p_T^\gamma \geq 10\text{ GeV}$

$N_{\text{tot}} = 2157$

$N_{\text{tot}} = 6350$

Good luck!

The photon in the event pushes the ST candidates out of the acceptance!!!



Outline

1. Introduction

- Pillars of the Energy Frontier
- MuC strong candidate for both

2. Minimal WIMPs

- Properties
- Projections

3. Soft Tracks

- Signal Regions
- Background Determination

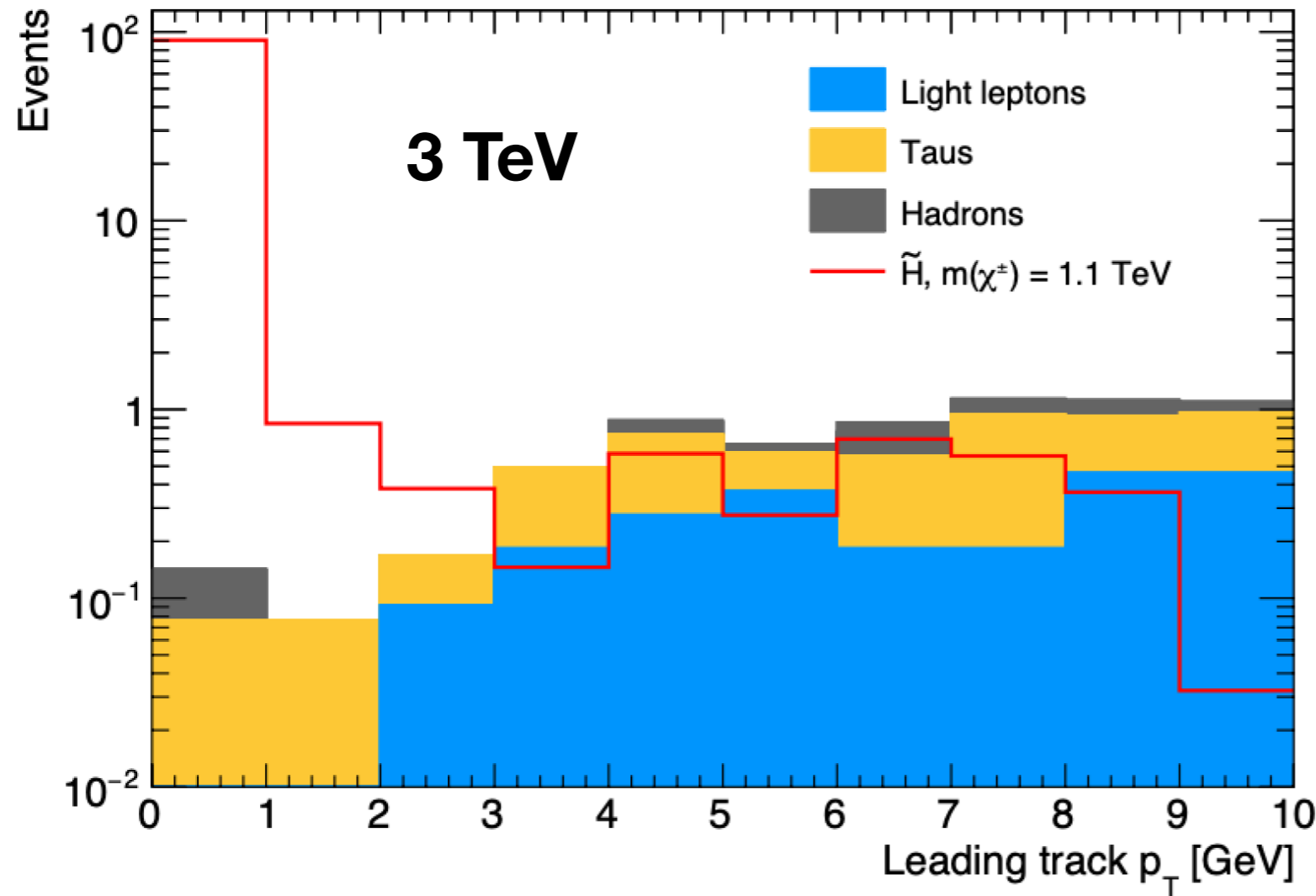
4. Results

- **The Importance of the 3TeV MuC!**

5. Discussion/Summary

4. Results

- The Importance of the 3TeV Collider:



Signal region:
2 ST + 1 gamma
 $0.3 < p_T < 1$ GeV

Vetoed:
Hard tracks
Heavy neutrals

Photon p_T above
20 GeV

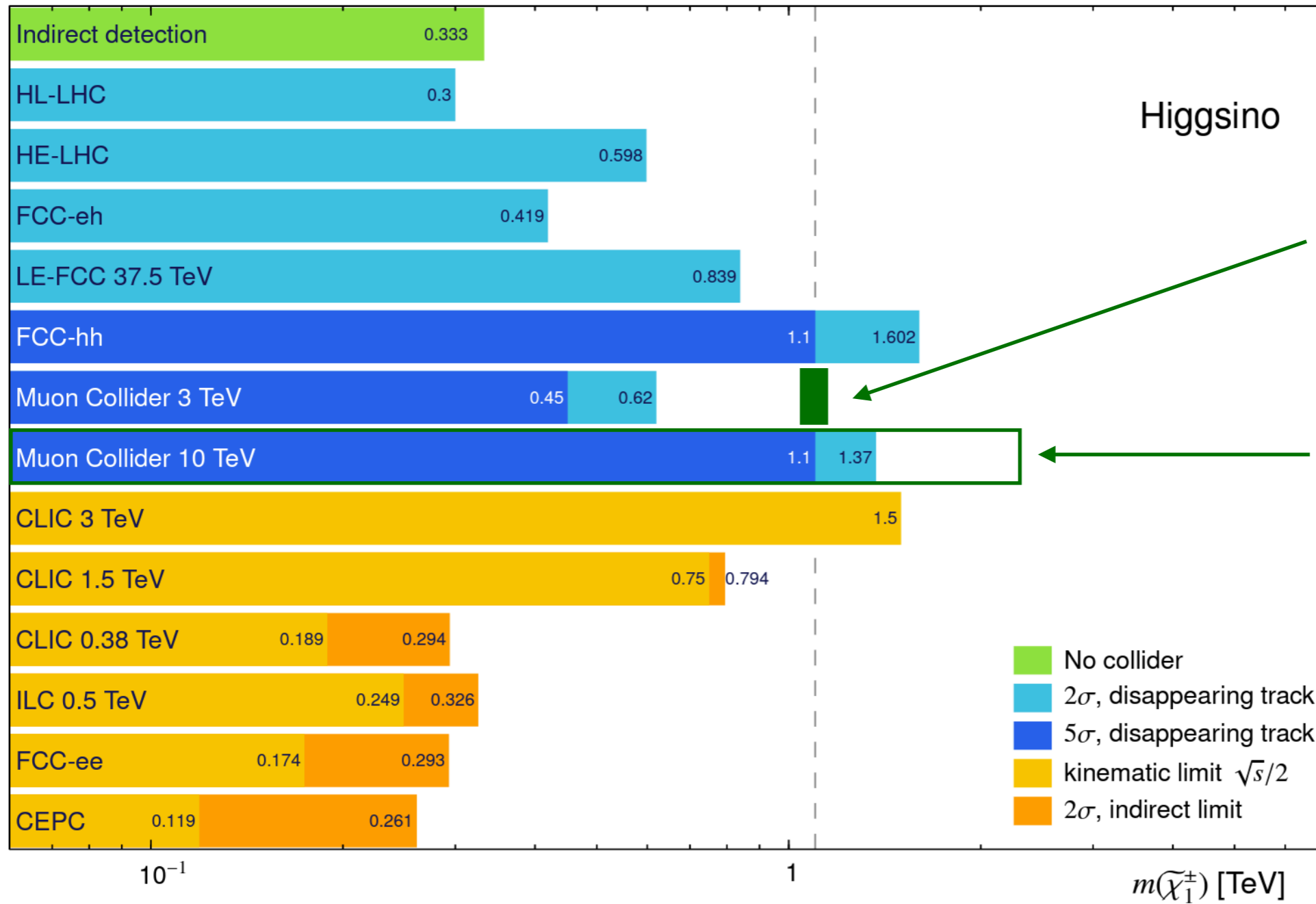
Fakes:

Pairs of ST along with
an uncorrelated photon

Random ECAL hits
from the BIB that can
mimic a photon

4. Results

- Projections:



The thermal target will be discovered!

Updated results from Federico Meloni's Disappearing Tracks

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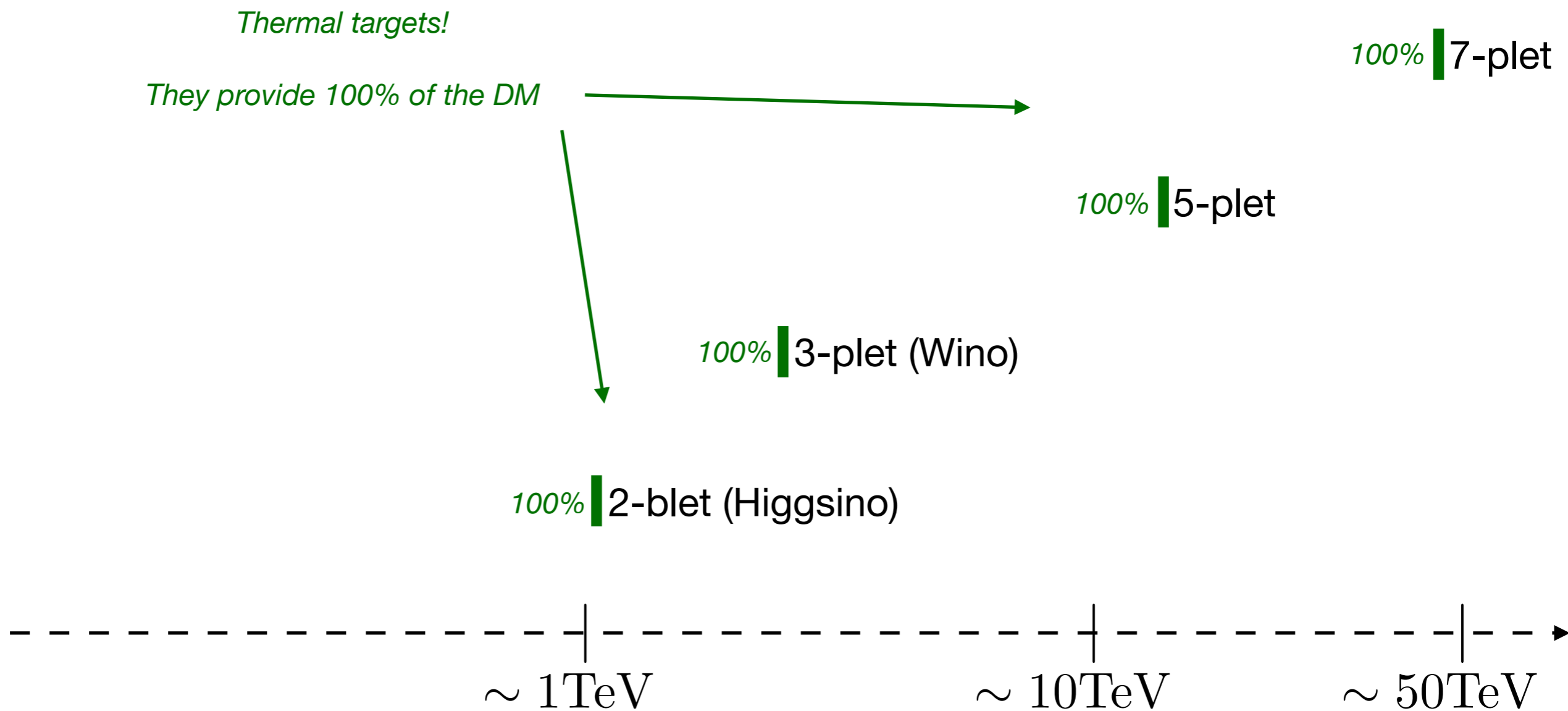
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- The Importance of the 3TeV MuC!

5. Discussion/Summary

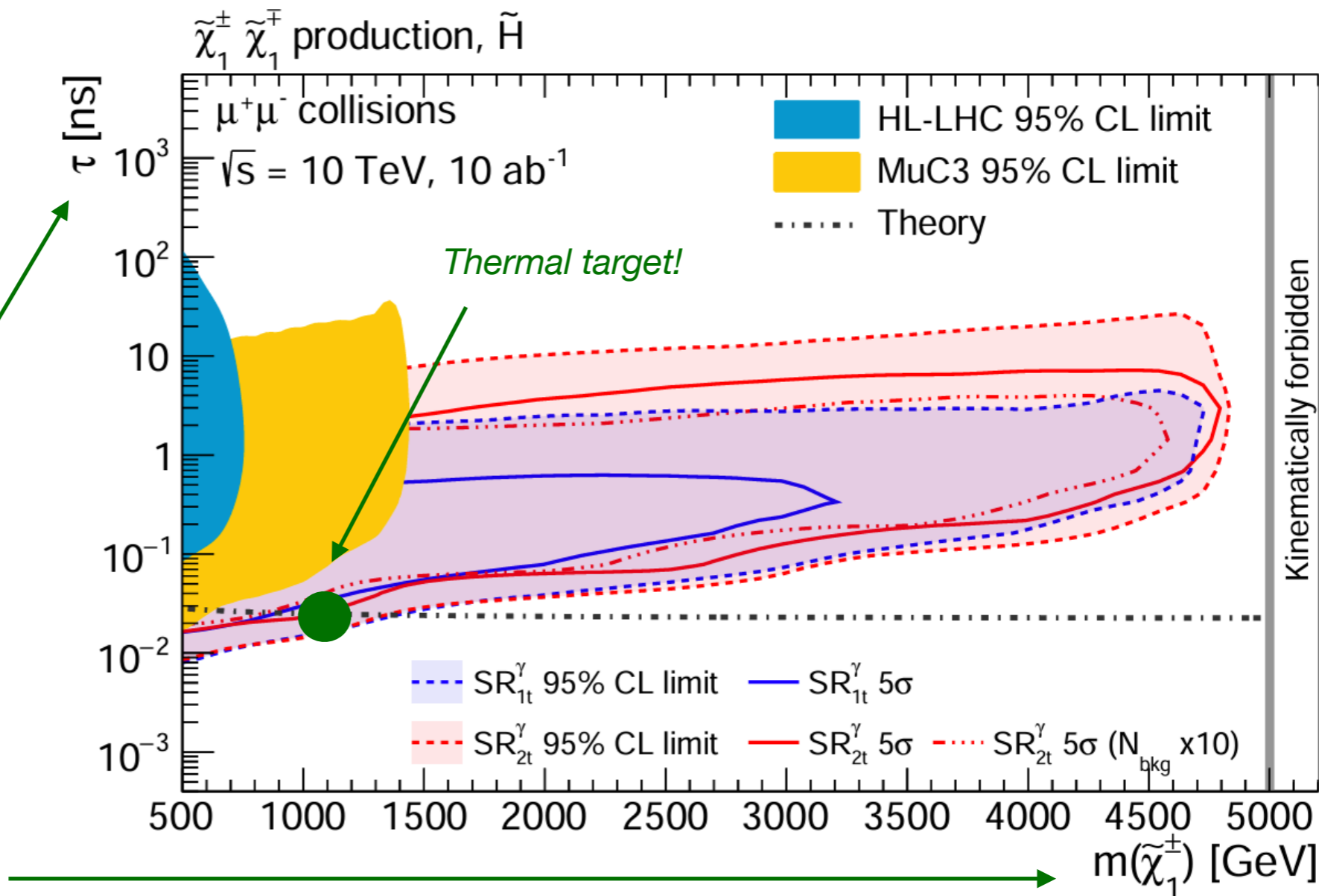
5. Discussion

- Minimal WIMPs:



5. Discussion

- Minimal WIMPs:

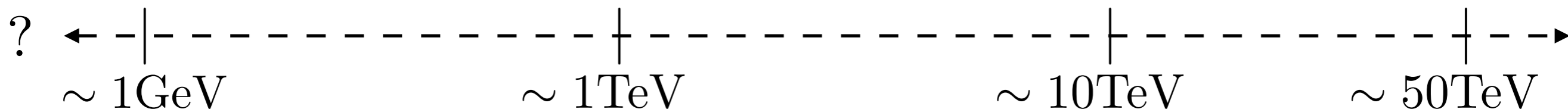
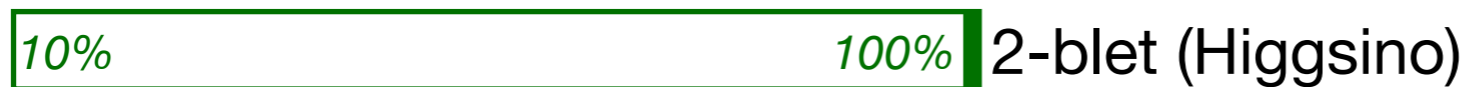


We typically study arbitrary masses and lifetimes

This is great, the projections can be used in the context of model that might not have anything to do with DM

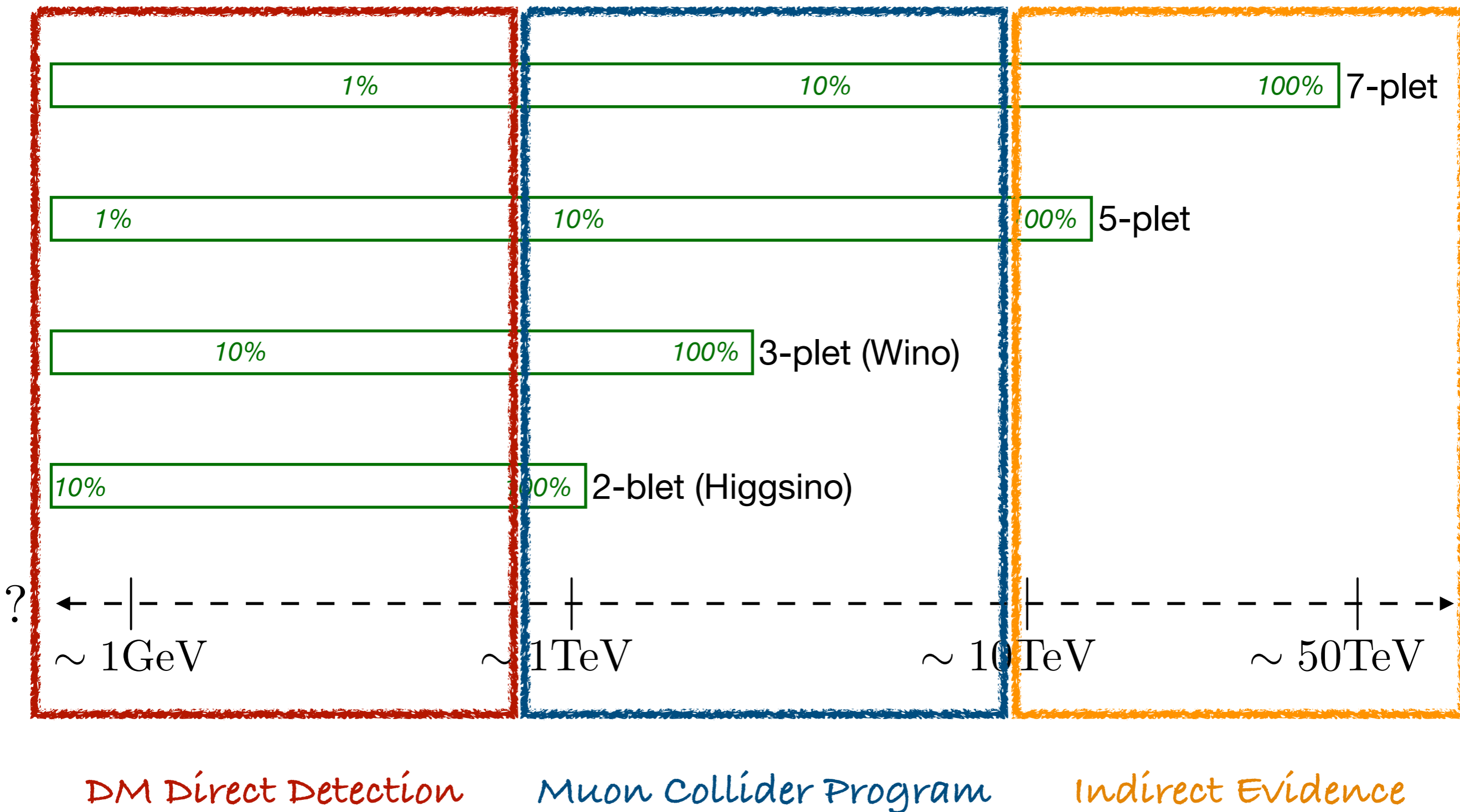
5. Discussion

- Minimal WIMPs:



5. Discussion

- Minimal WIMPs:



Summary

1. Exotic signals from motivated BSM particle candidates may have an impact on detector design. Theorists and Experimentalists are currently working on developing signal efficiency maps that would allow the HEP community to perform accurate projections for the Muon Collider physics program.
2. Soft Track searches will be possible at the Muon Collider. Using this technique **the 3TeV Muon Collider has the potential of discovering the thermal Higgsino-like minimal WIMP**. This result suggest that the 3TeV Muon collider is not only a stage to the 10TeV machine but it is also a powerful discovery machine.
3. The Muon Collider program (3 -> 10 TeV) will be able to discover and characterize minimal WIMPs. A combination of Disappearing Track and Soft Track searches will allow us to determine the mass of the thermal relic, as well as the mass gap between this particle and its companion charged state.

Thank You!